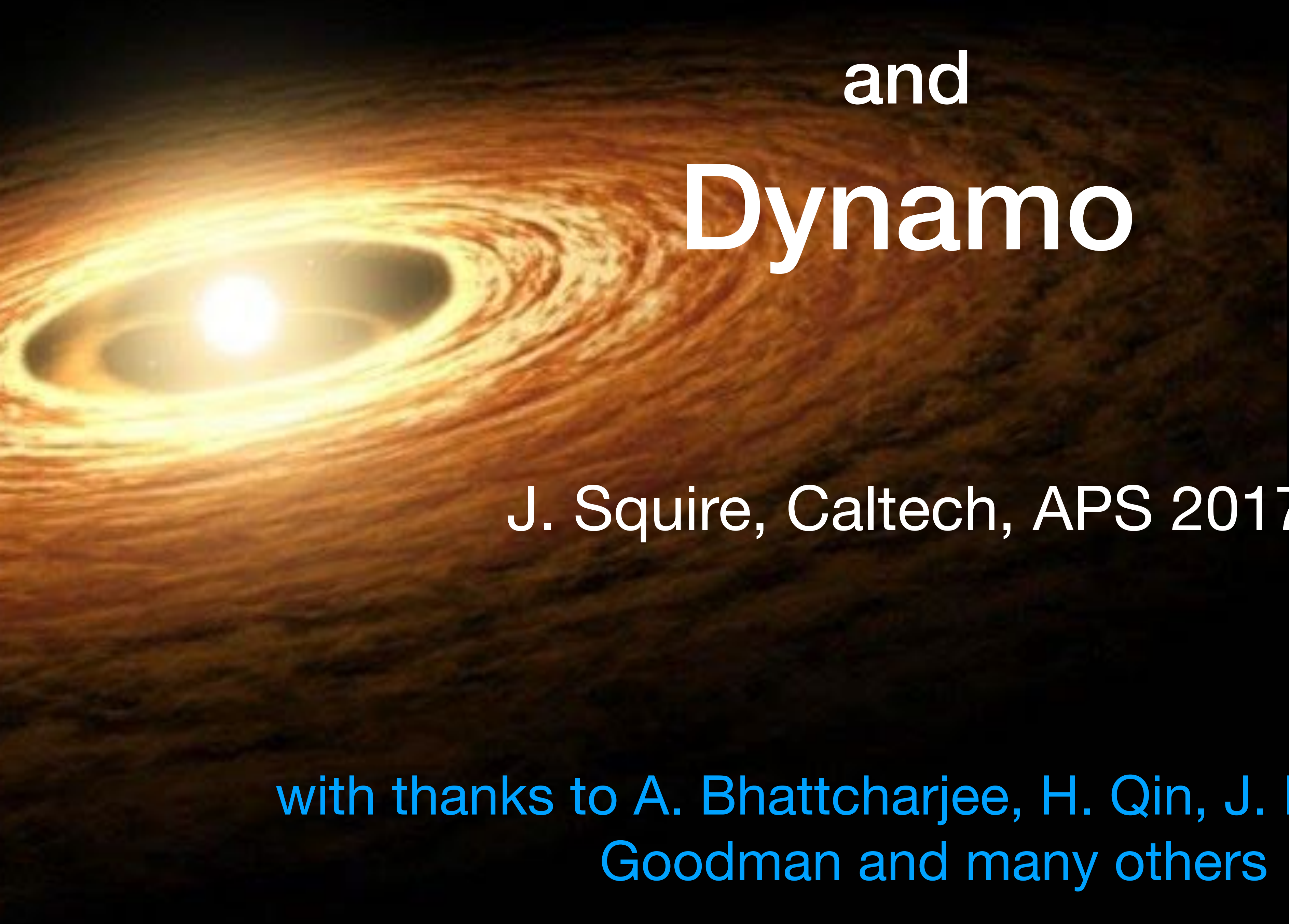
Magnetorotational turbulence

and

Dynamo



J. Squire, Caltech, APS 2017

with thanks to A. Bhattcharjee, H. Qin, J. Krommes, J. Goodman and many others

Astrophysical disks

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- As matter falls in gravity, cannot lose its angular momentum

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A DISK STRUCTURE

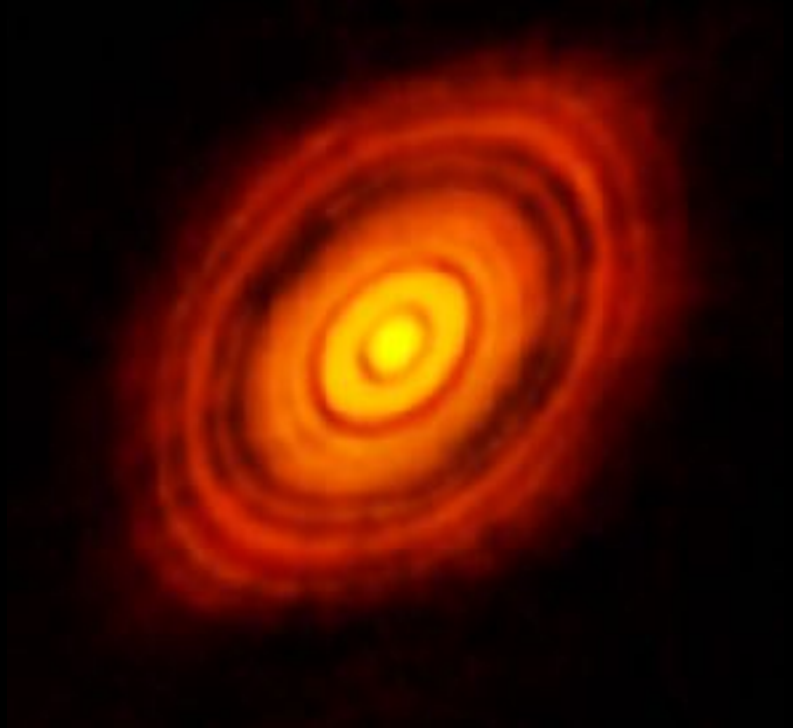
Astrophysical disks

- Disks are everywhere
- As matter falls in gravity, cannot lose its angular momentum

A DISK STRUCTURE

- Can be very bright! Possible to convert ~1/2 of gravitational energy into radiation

Source: ALMA Collaboration

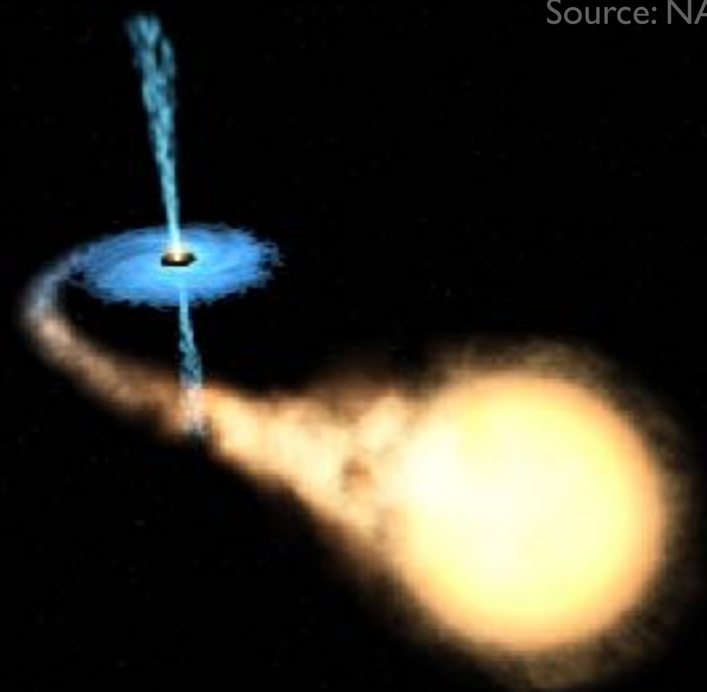


PROTOPLANETARY DISKS

Disks around young stars.

Site of planet formation.

Source: NASA



BINARY SYSTEMS

Star looses matter to companion object (black hole, neutron star, white dwarf).

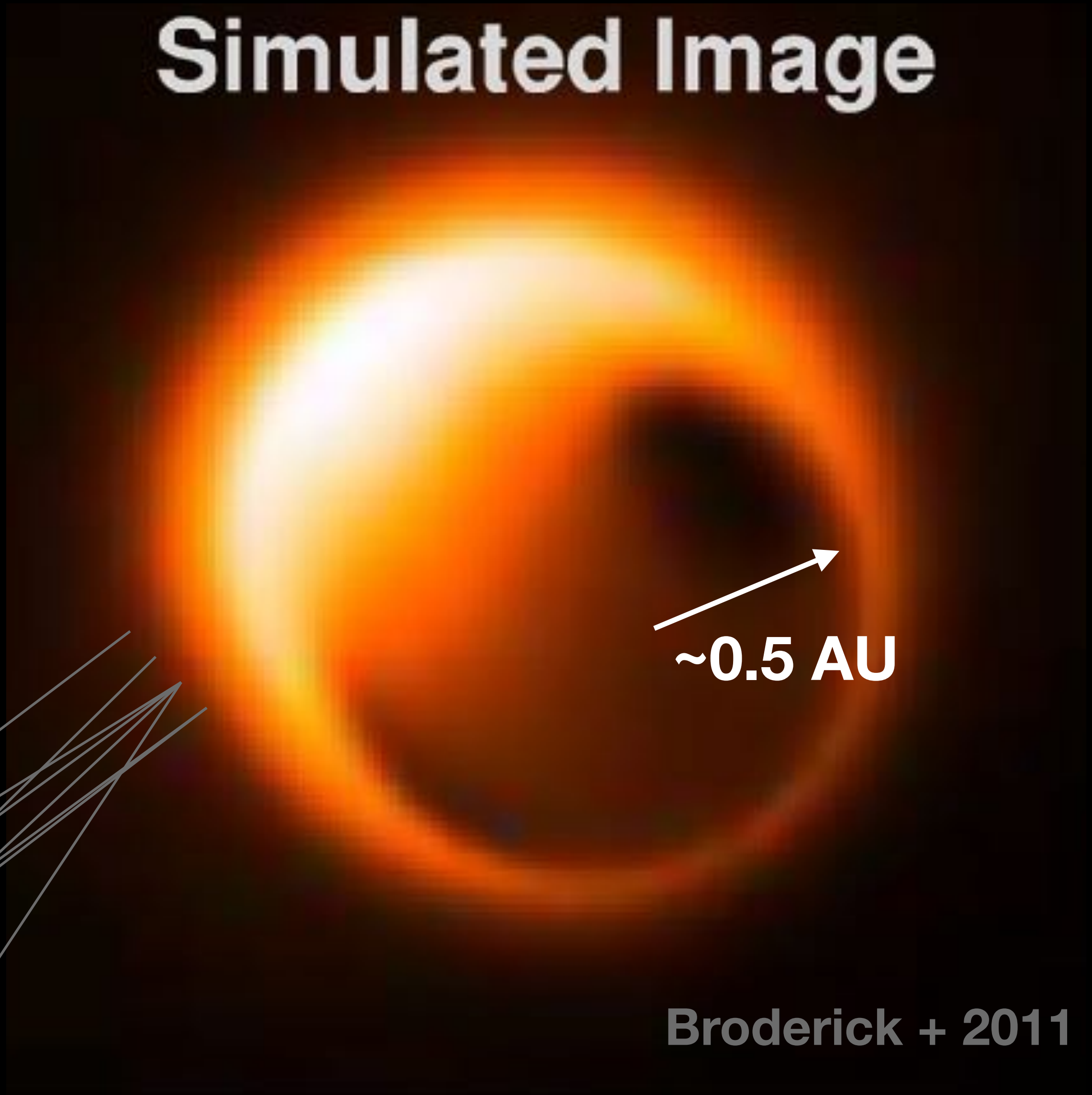
Source: NASA

GALACTIC NUCLEI

Supermassive black hole at the center of a galaxy.

Active nuclei can outshine entire galaxy!

We will soon see the accretion disk around the black hole at the center of our galaxy

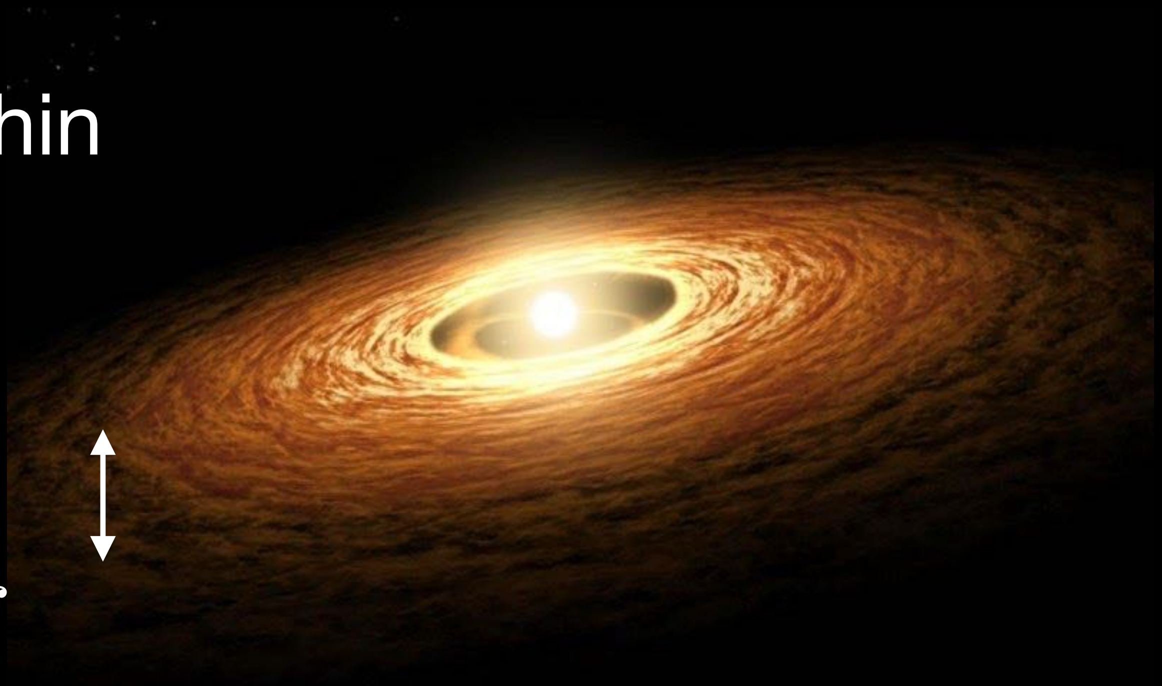


Event Horizon Telescope

Basic physics

Thin disks

- Most disks cool efficiently
- Plasma energy dominated by rotational rather than thermal
- Disk is thin



$H \ll r$

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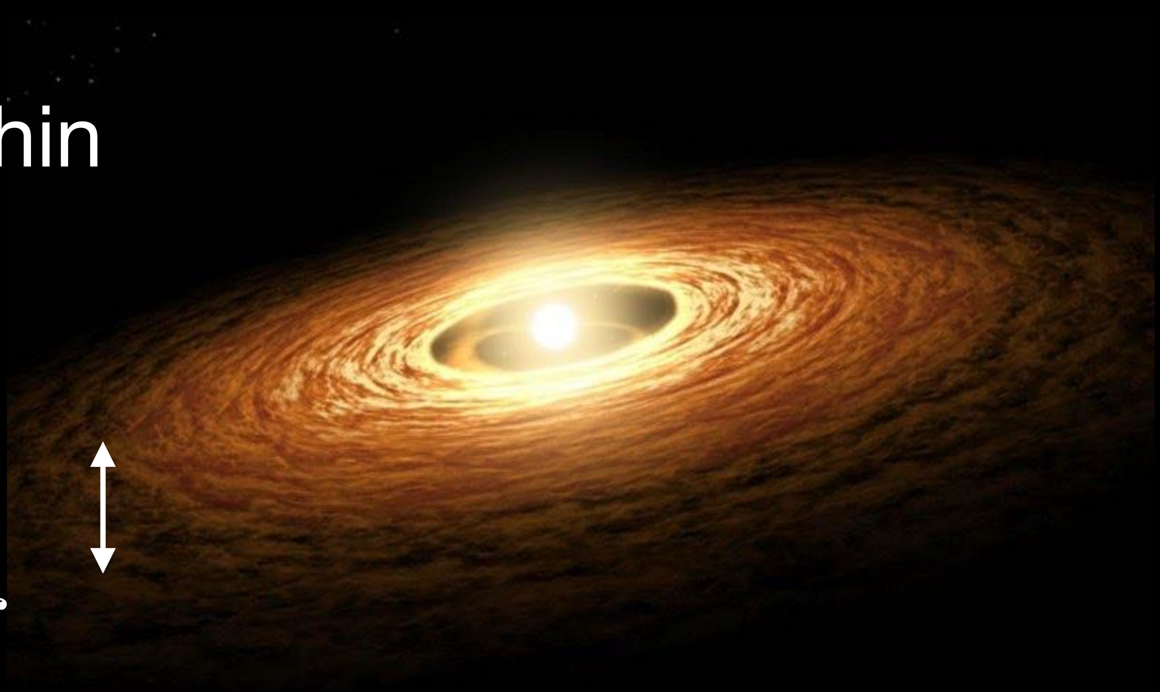
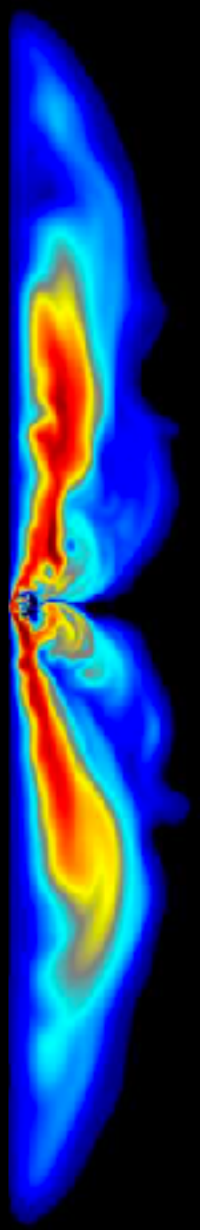


$H \ll r$

Thick disks

- If it cannot cool, disk puffs up.
- Advection dominated flow

$T \gtrsim 10^{10}\mathrm{K}?$



S. Noble + (2007)

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- Angular momentum is conserved — no sources and sinks

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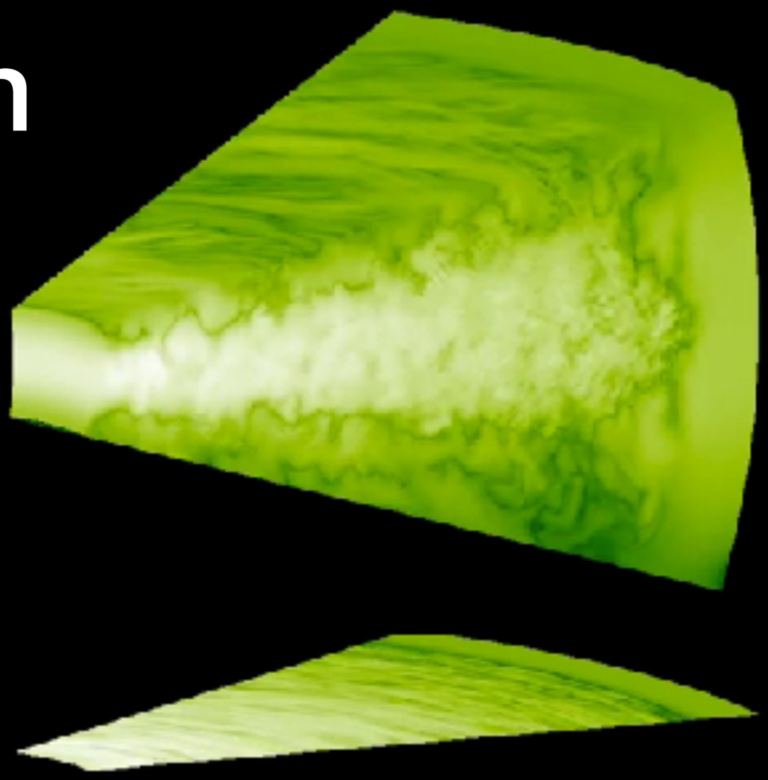
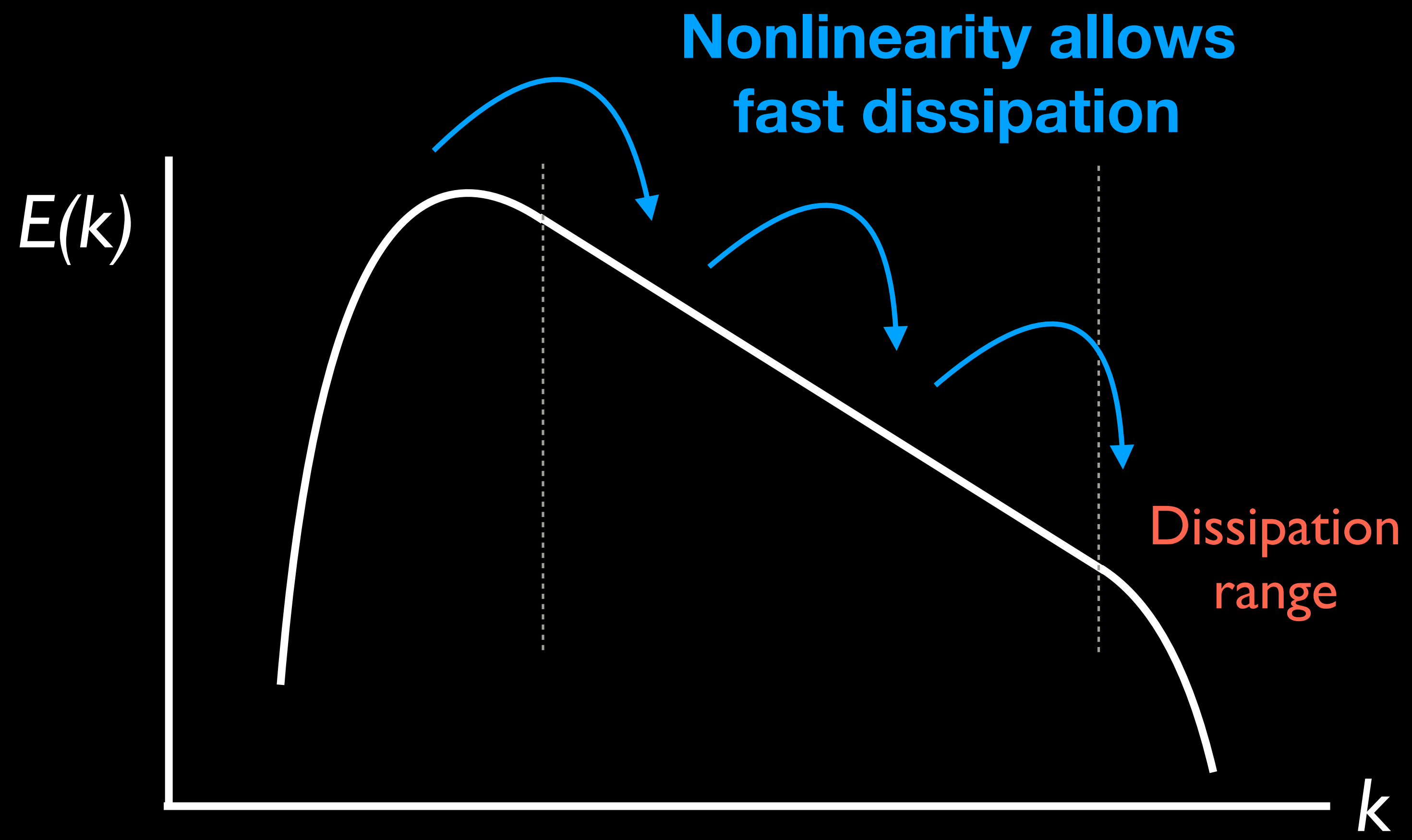
- Angular momentum is conserved — no sources and sinks
- Circular Keplerian orbits — no energy lost and no radiation? Obviously not reality….

Turbulence provides a solution



- Accretion rate can be large and independent of viscosity



Credit: V. Lyra, youtube.com

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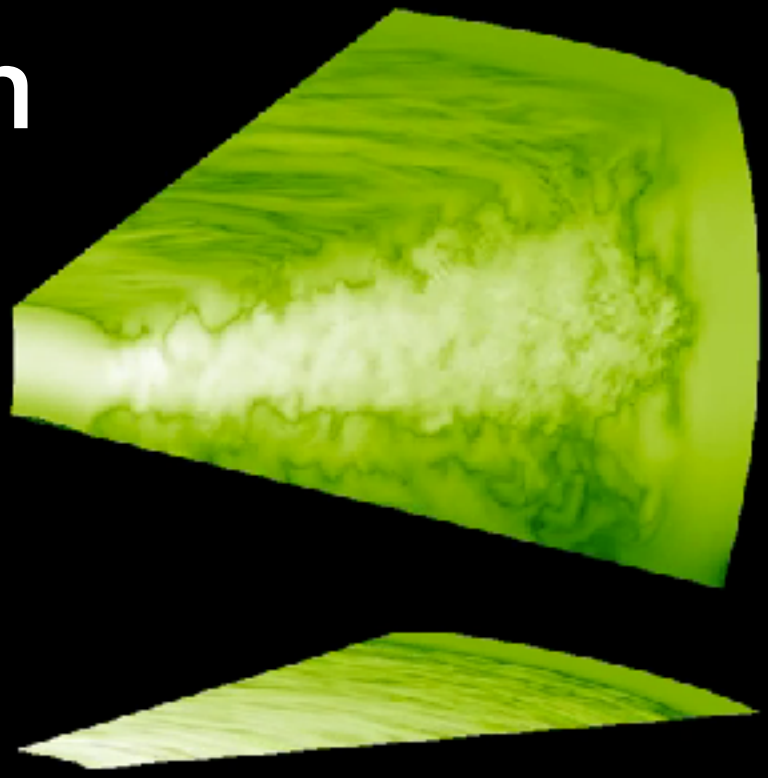

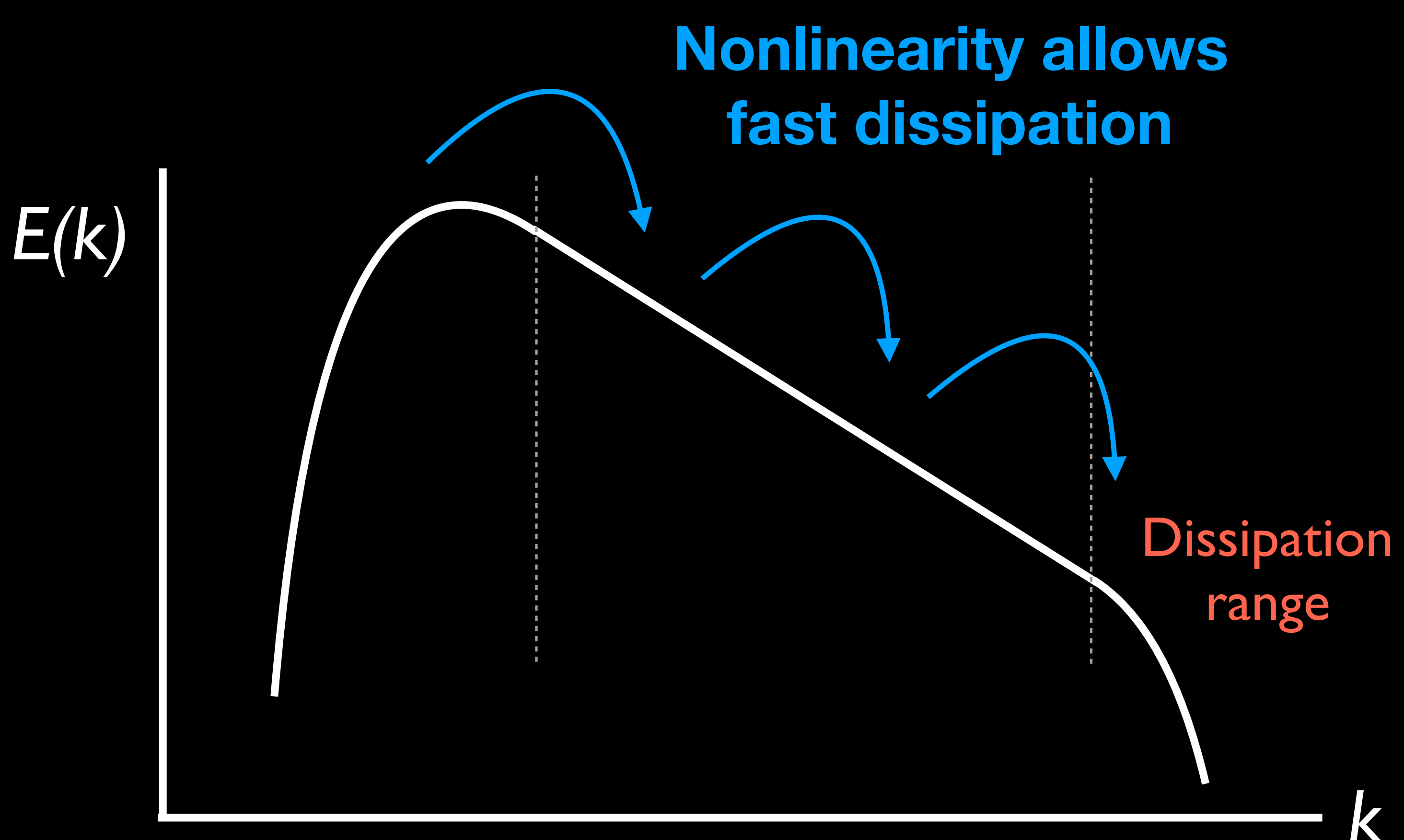

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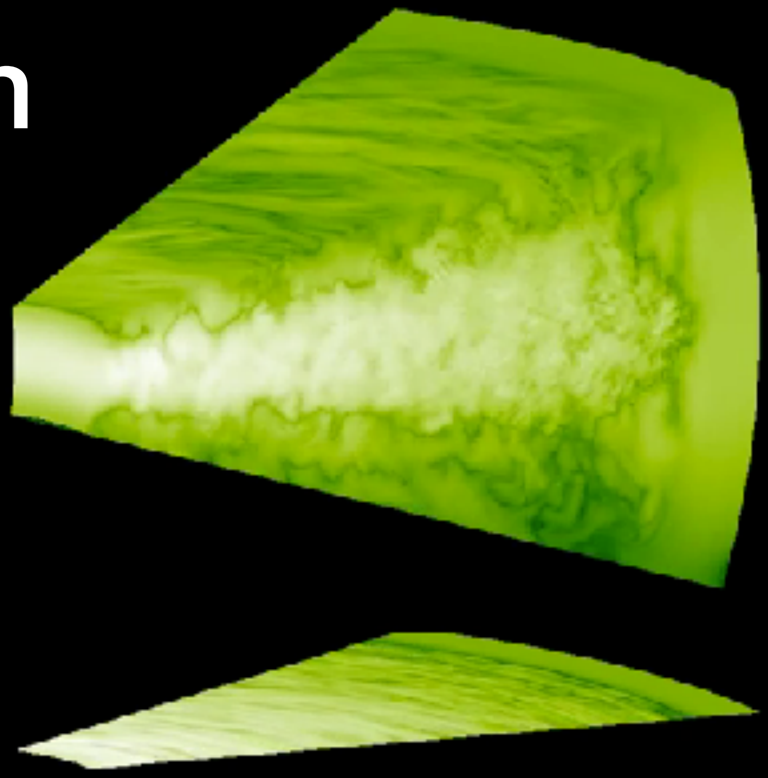

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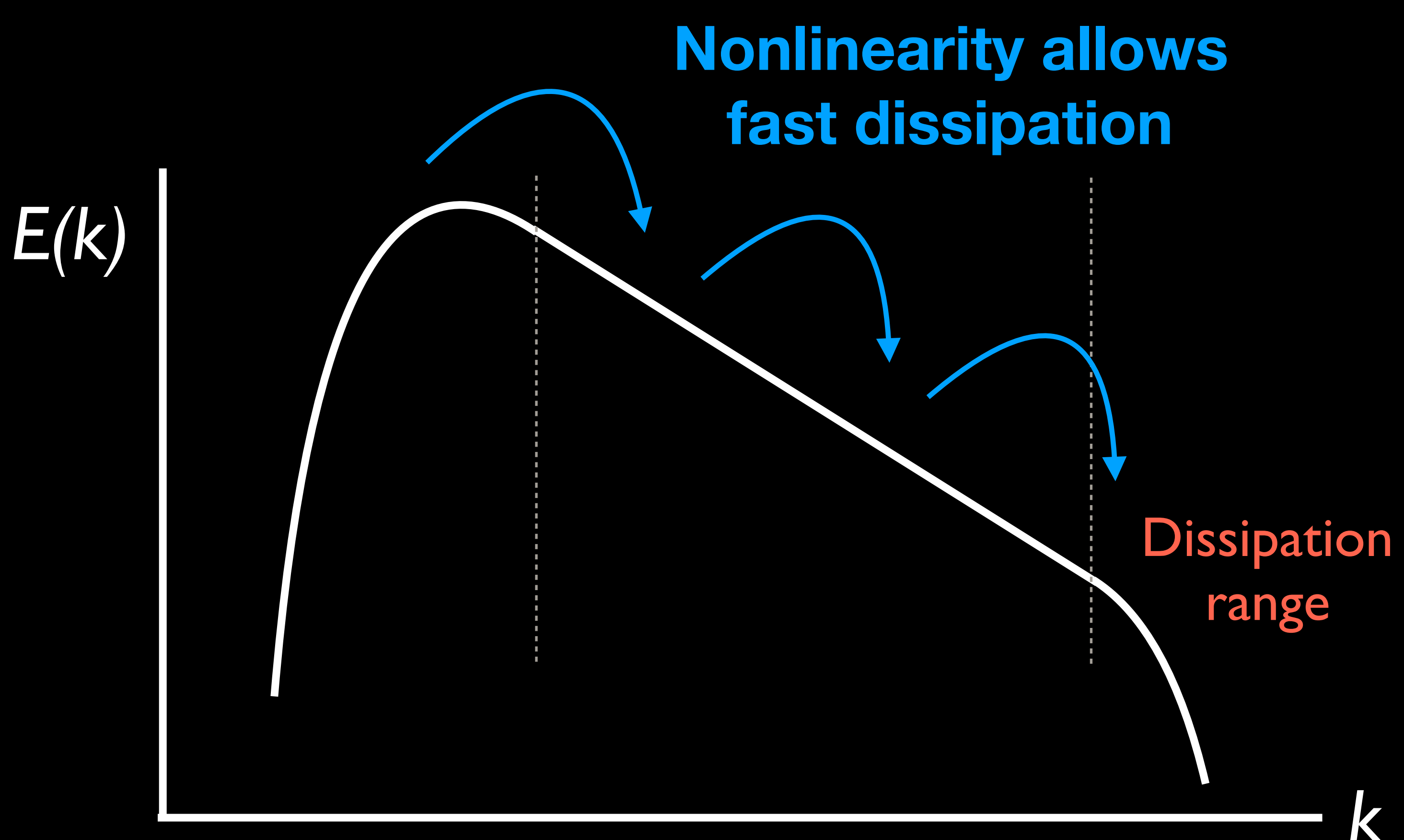
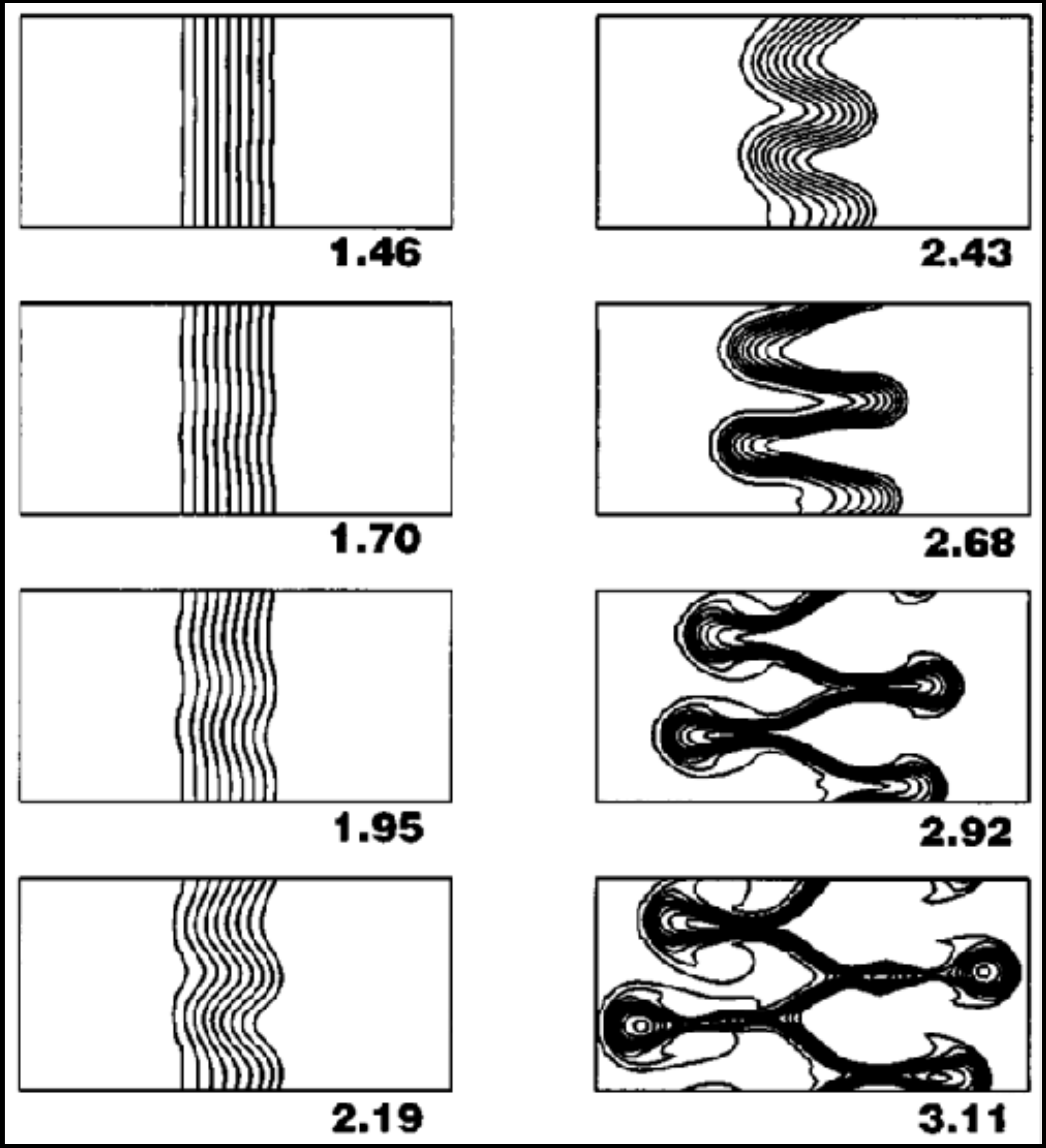


- But Keplerian shear flows are nonlinearly stable?? (Ji + 2006)

This is why the magnetorotational instability matters

Balbus & Hawley 1991

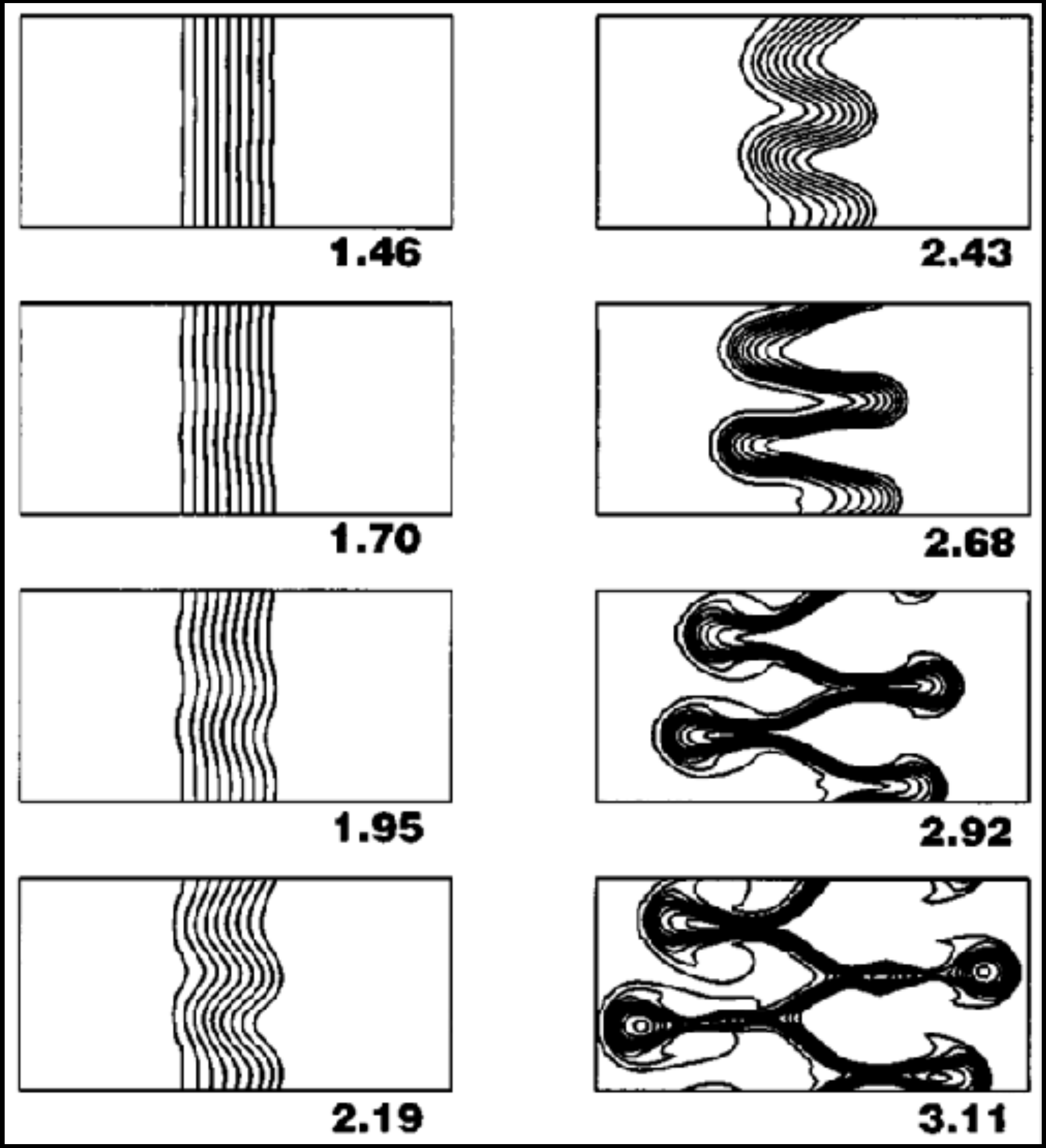


*Balbus & Hawley, RMP **70** 1 (1998)*

This is why the magnetorotational instability matters

Balbus & Hawley 1991

- Even tiny B fields are violently unstable



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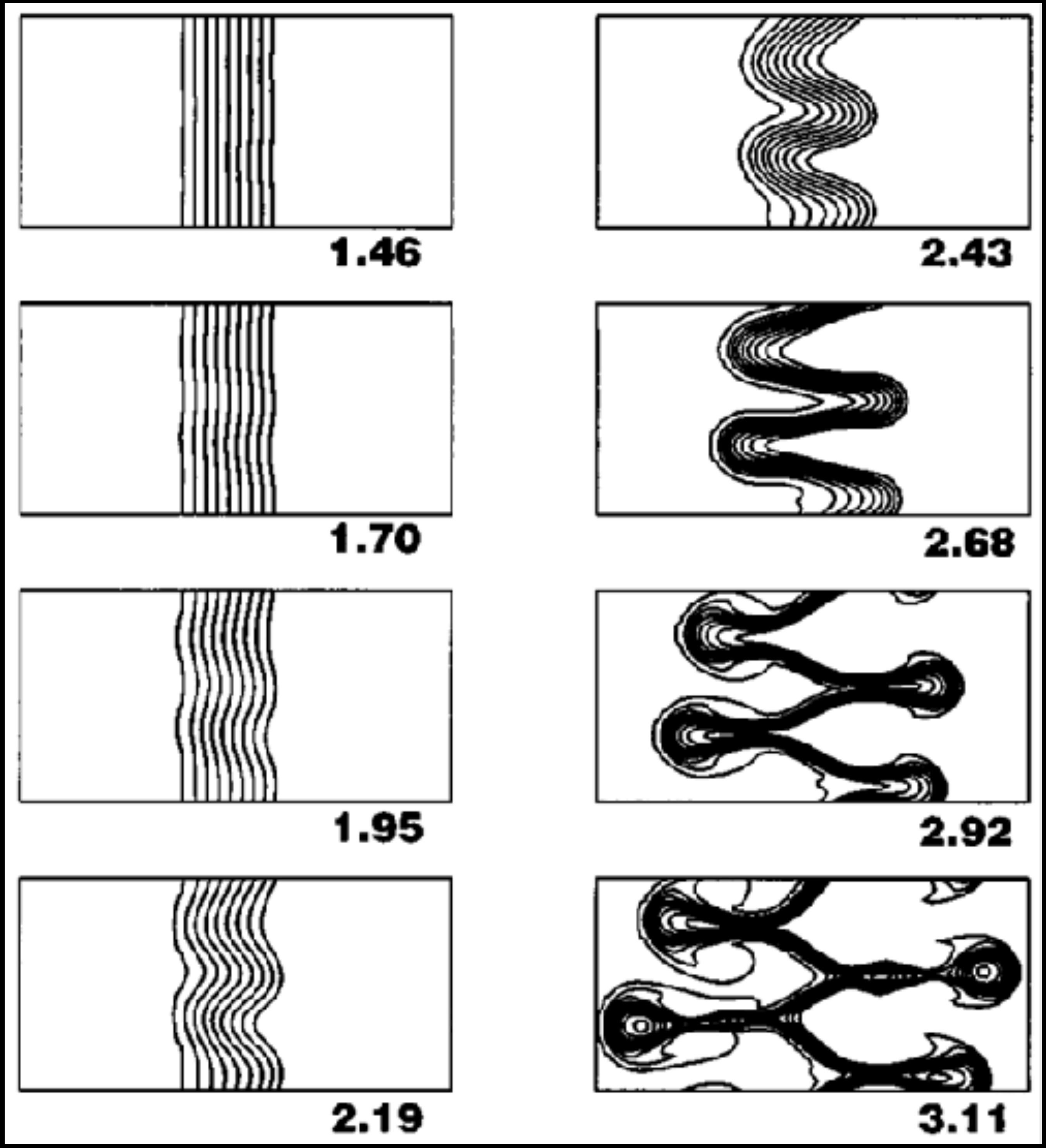
- Growth rate is fast, set by shear, $k \sim v_A/\Omega$

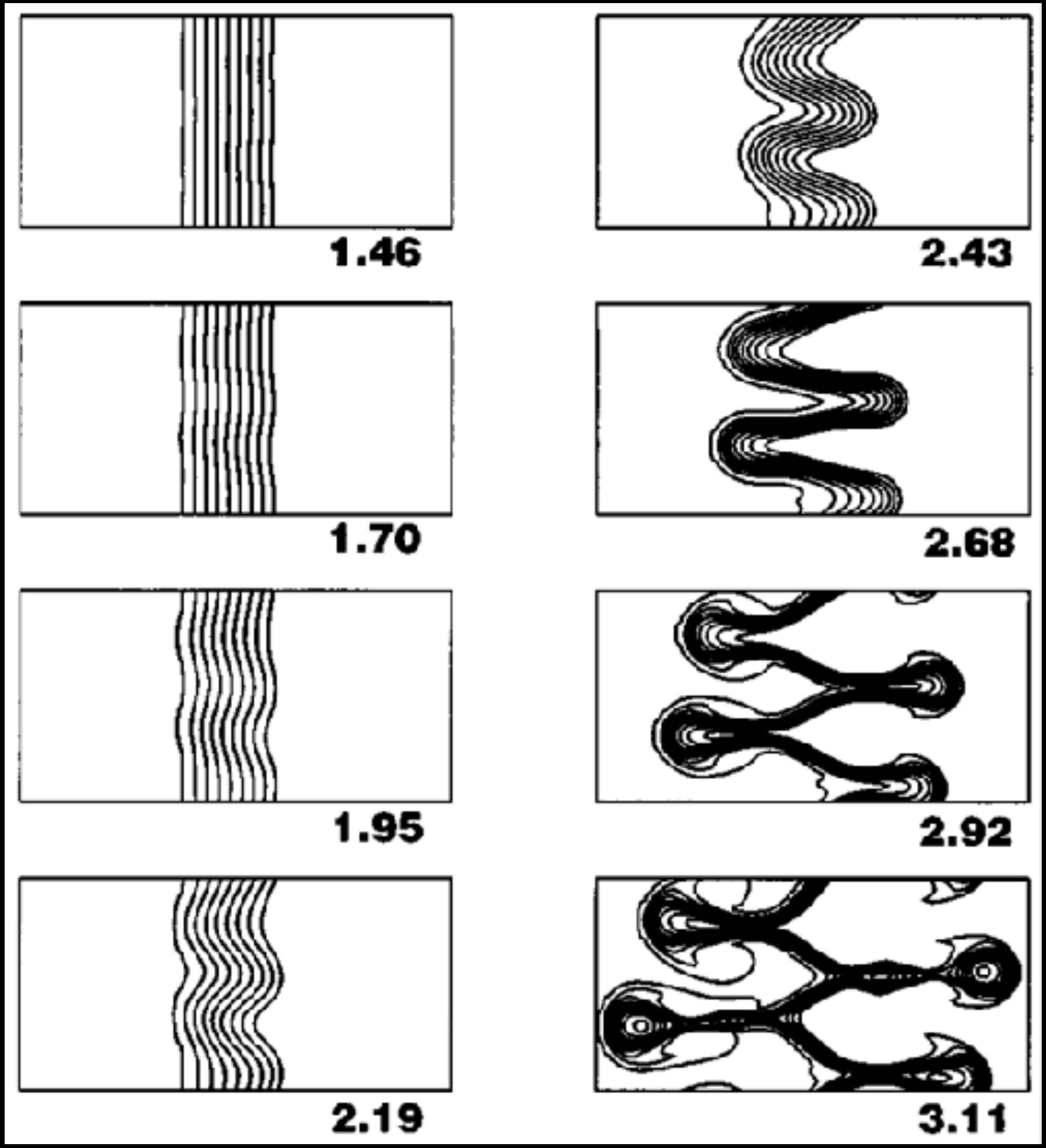


Balbus & Hawley, RMP ***70*** *1 (1998)*

This is why the magnetorotational instability matters

Balbus & Hawley 1991

- Even tiny B fields are violently unstable
- Growth rate is fast, set by shear, $k \sim v_A/\Omega$
- Creates turbulence



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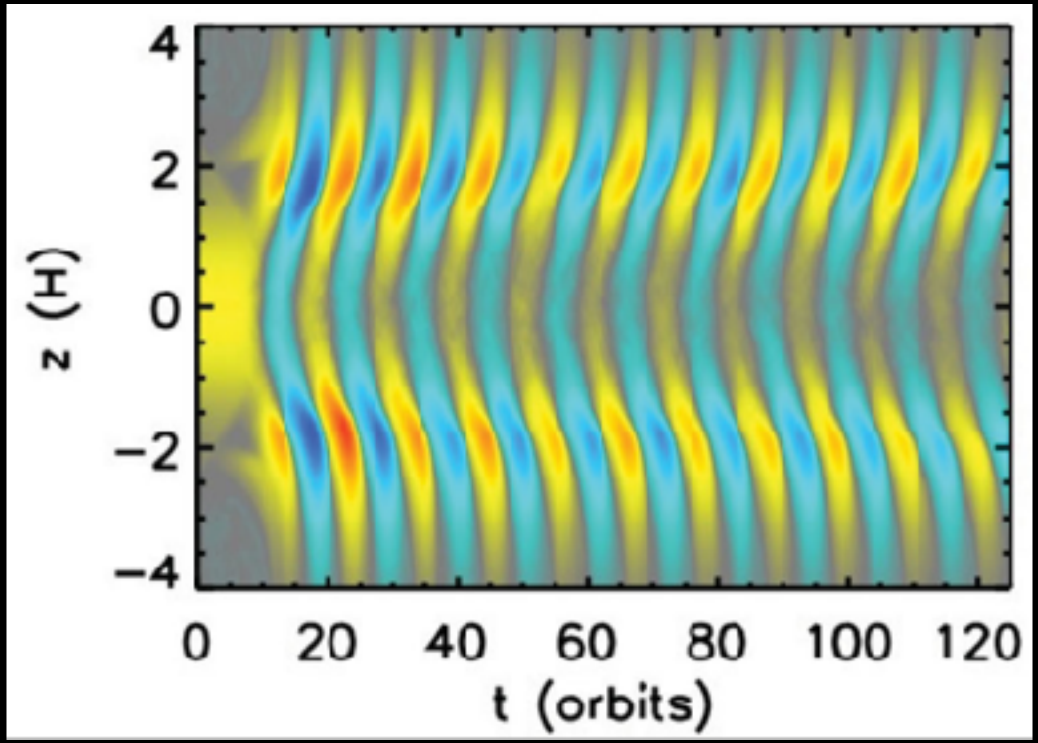
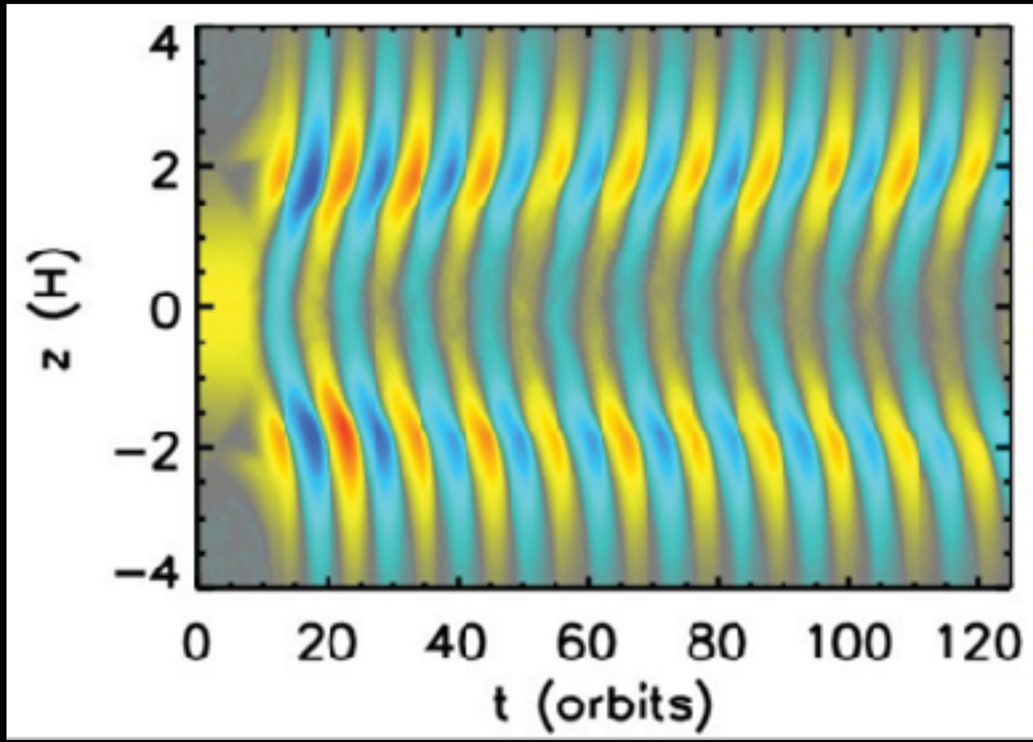
Simon et al., MNRAS ***422*** *2685 (2012)*



The turbulence has interesting properties:

- Self sustaining, but depends on microphysics
- Generates large-scale magnetic fields
- Even seems similar in a collisionless plasma (Kunz + 2016) so likely ubiquitous

Simon et al., MNRAS **422** *2685 (2012)*



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Fromang+ 2007

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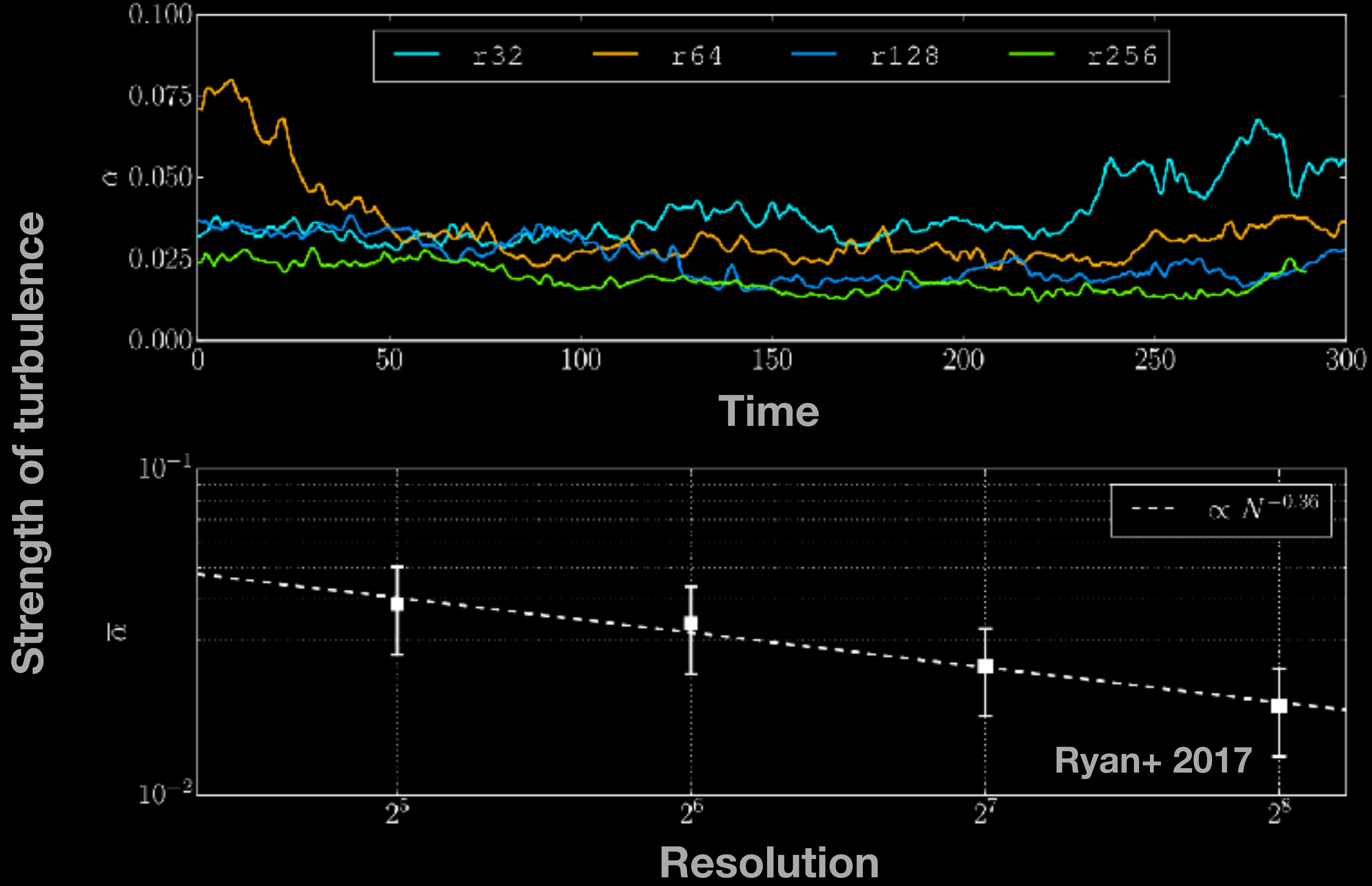

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Fromang+ 2007b

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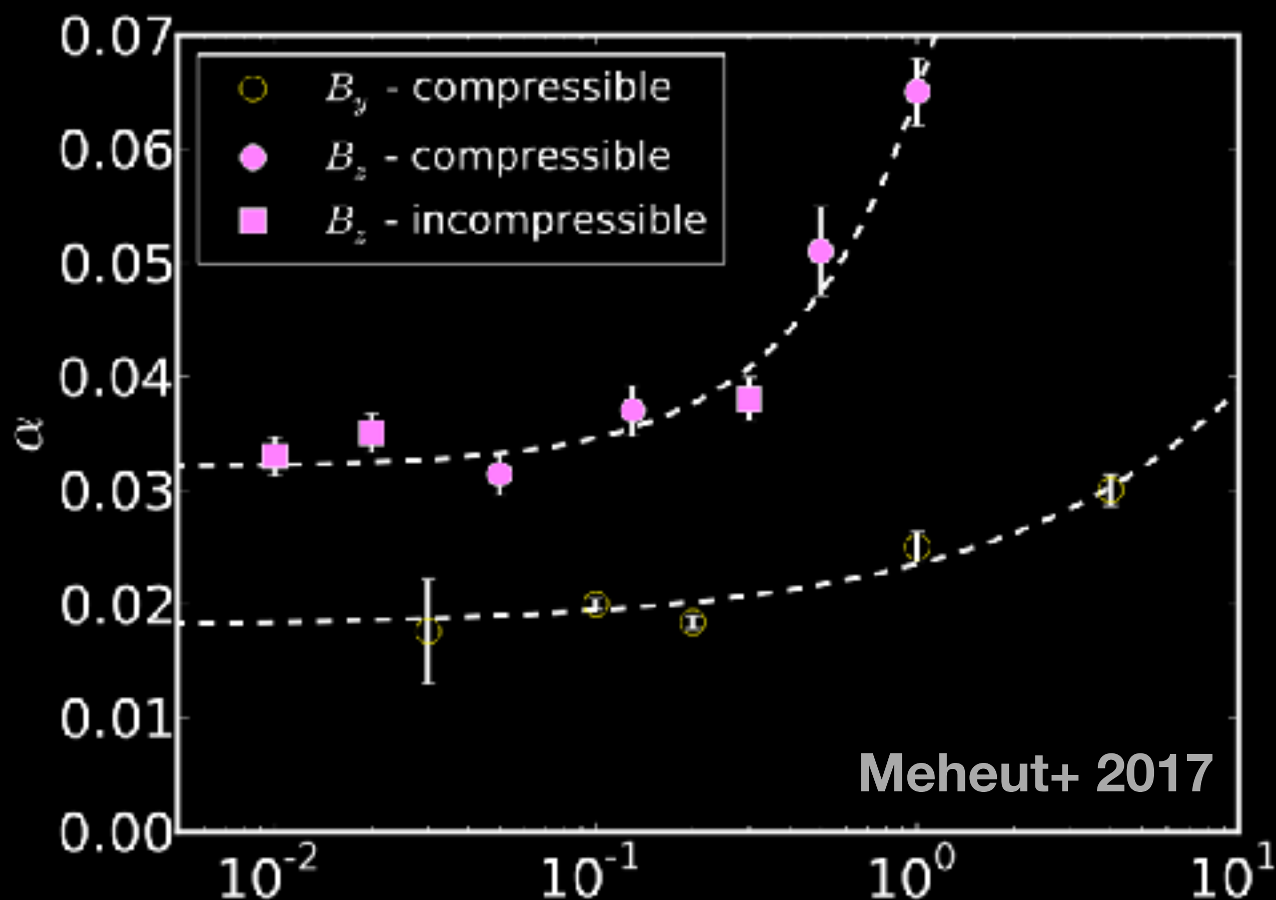

Pm = viscosity/resistivity

Questions:

Fromang+ 2007b

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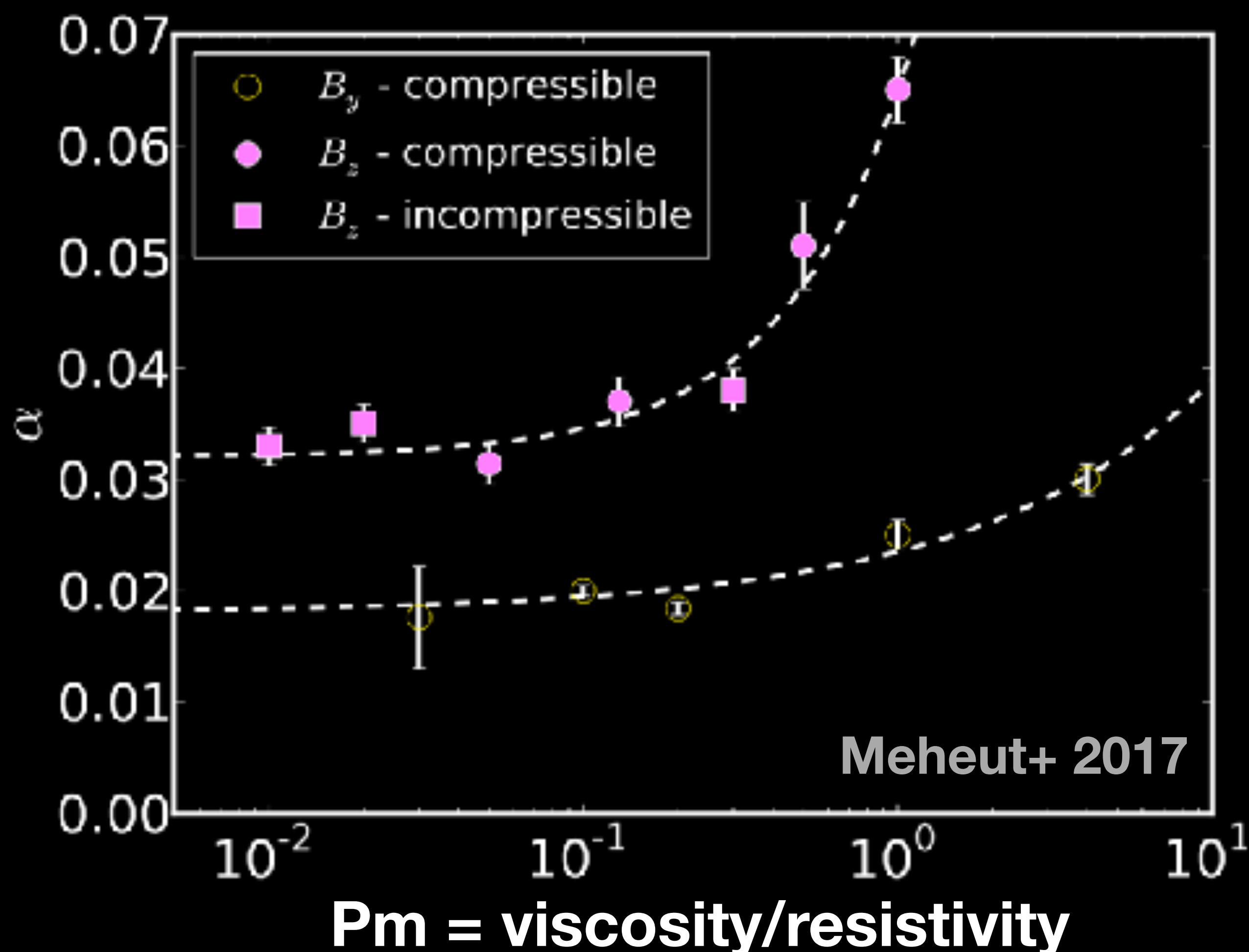

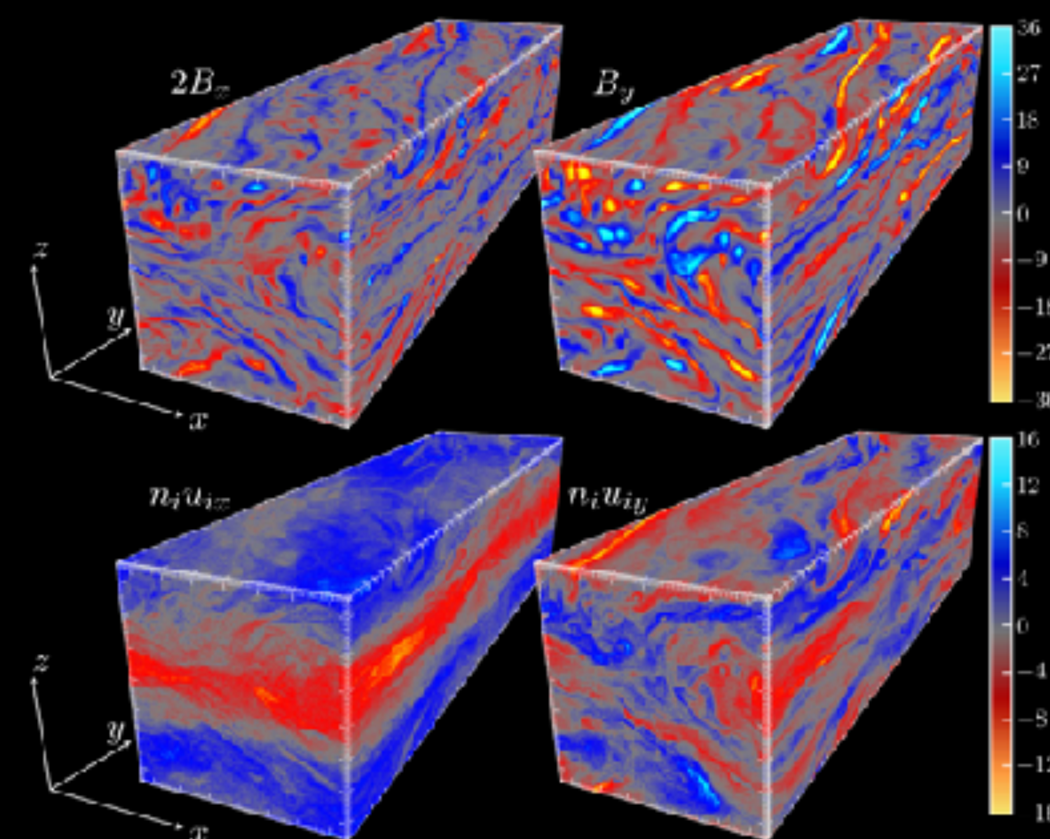

Kunz+ 2016

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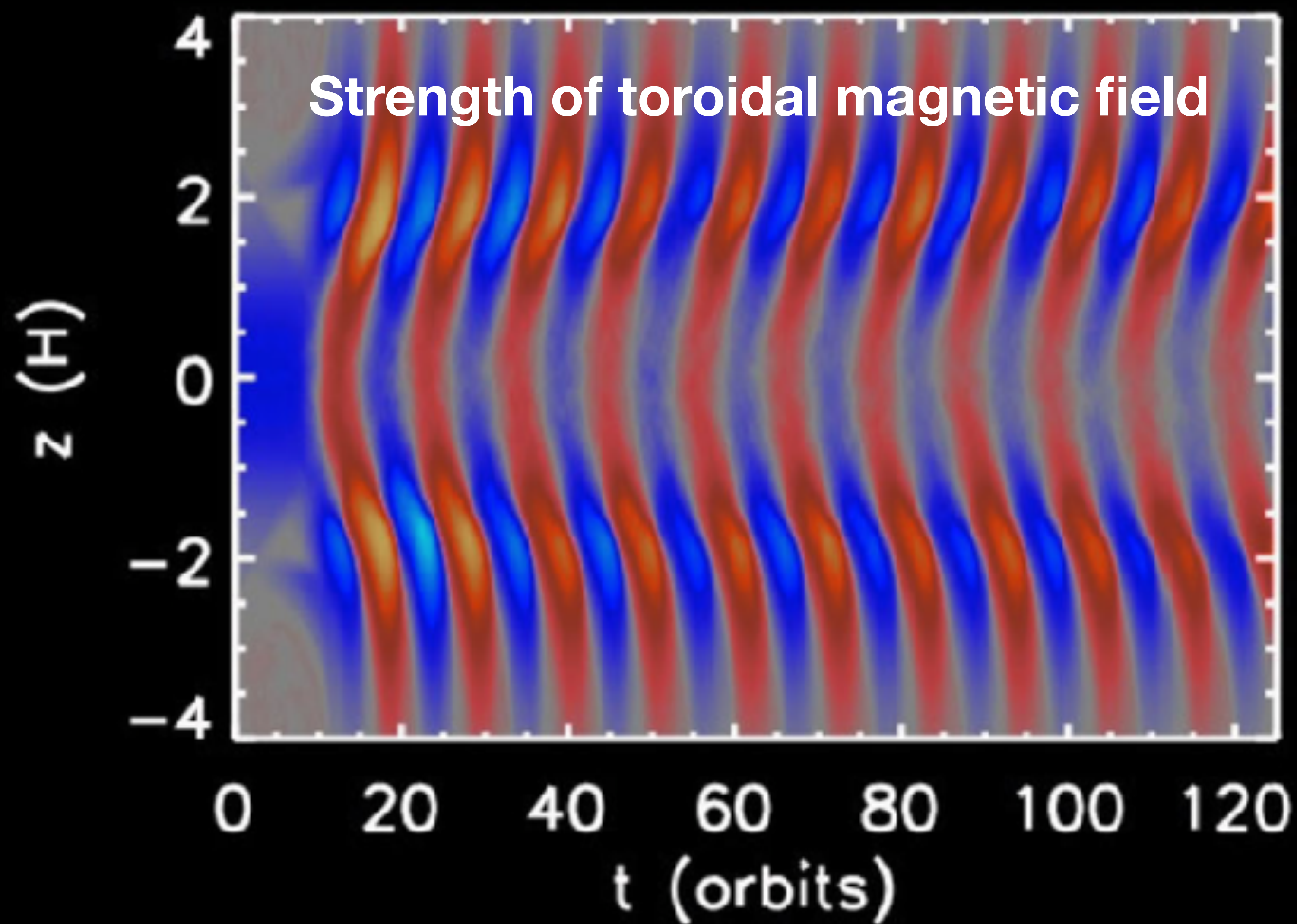
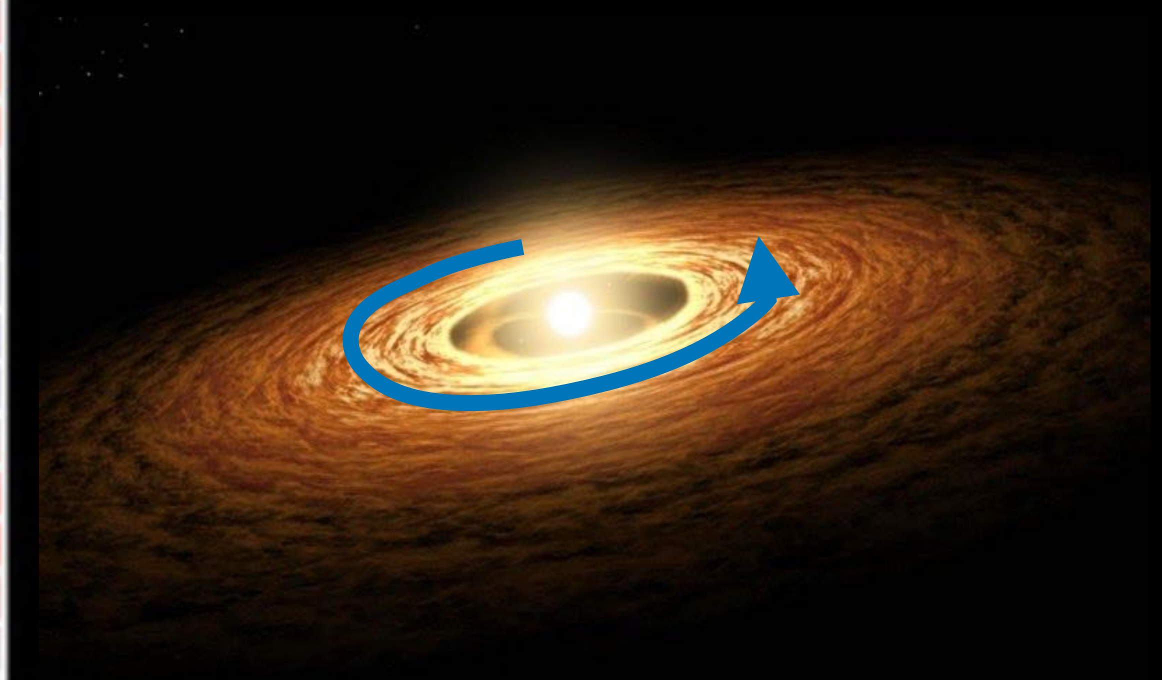
Simon+ 2012

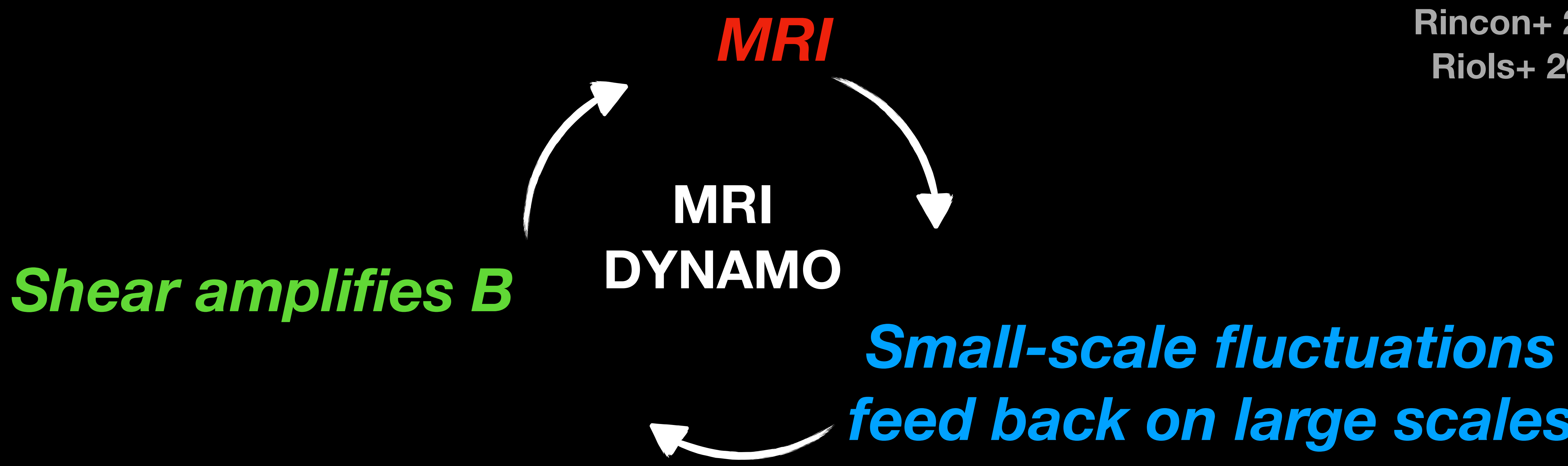




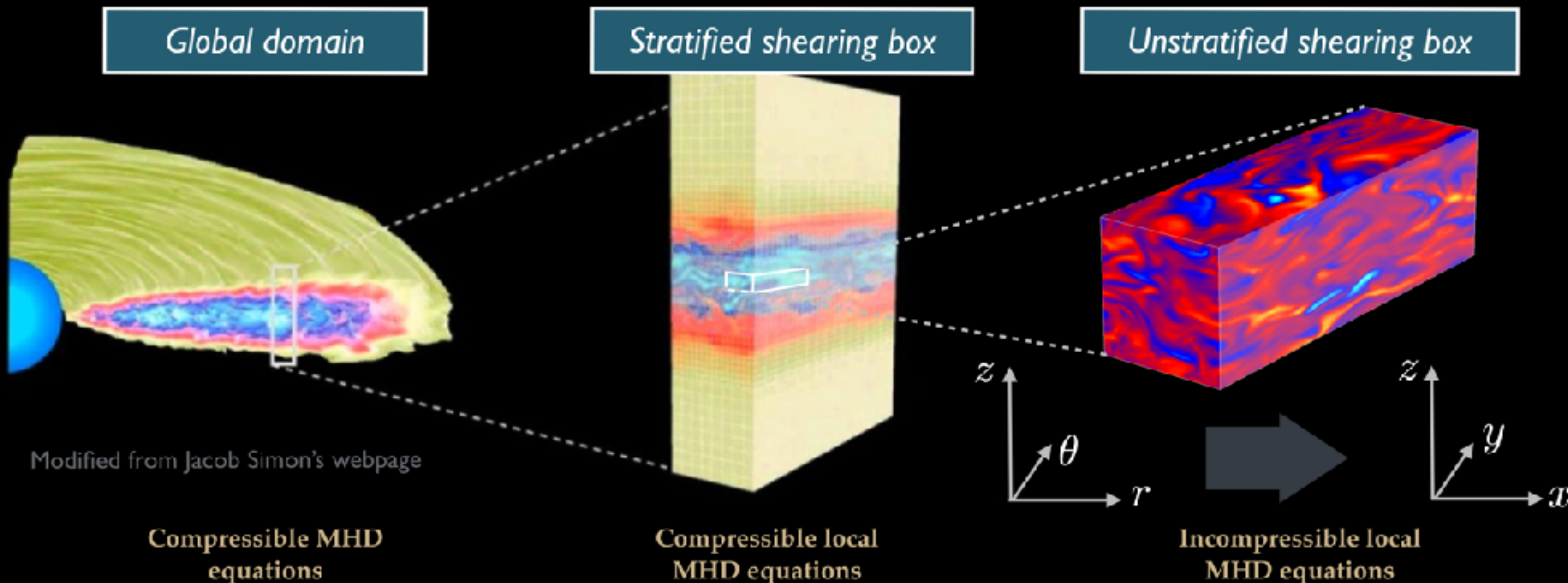
Lesur & Ogilvie 2008

Answers?

Rincon+ 2007
Riols+ 2015



Use simplest possible setup



Rincon+ 2007
Riols+ 2015

MRI

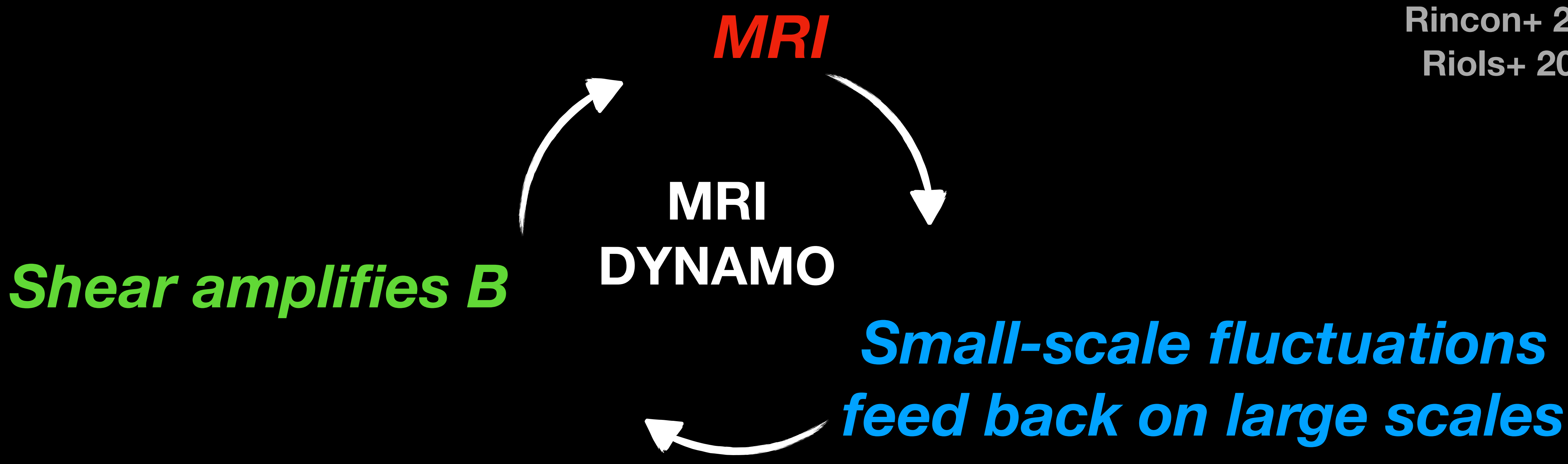
MRI
DYNAMO

Shear amplifies B

Small-scale fluctuations feed back on large scales

Outline

Rincon+ 2007
Riols+ 2015



Outline

- Dynamos

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Outline

- Dynamos
- Magnetic shear-current effect

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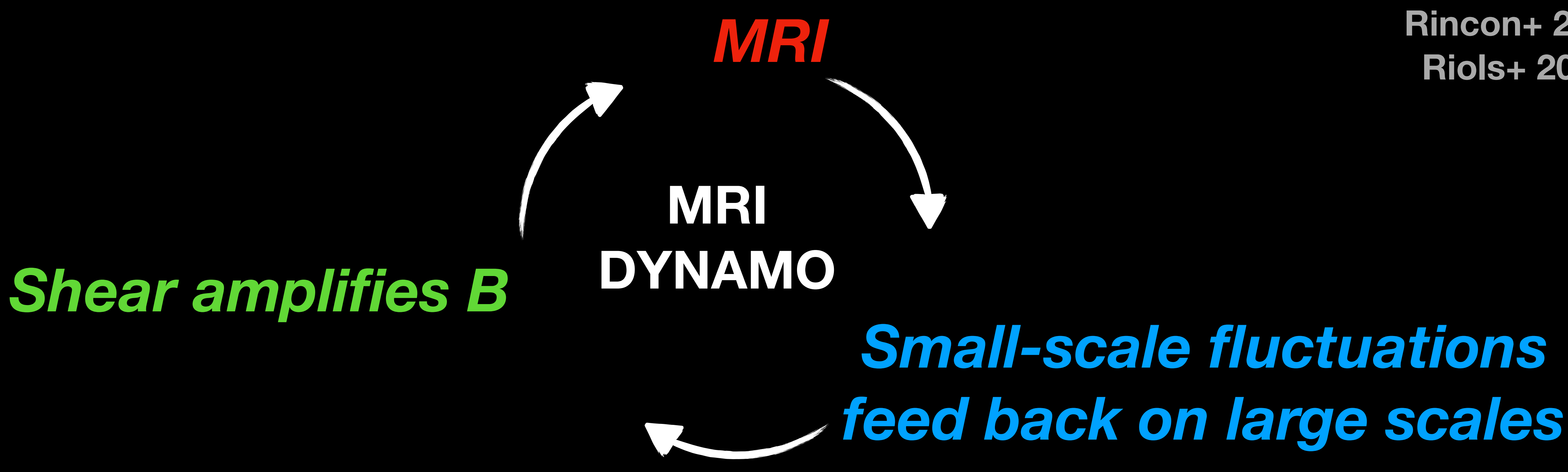

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- Dynamos
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Large-scale dynamo

- Thought experiment: given some smaller-scale turbulence

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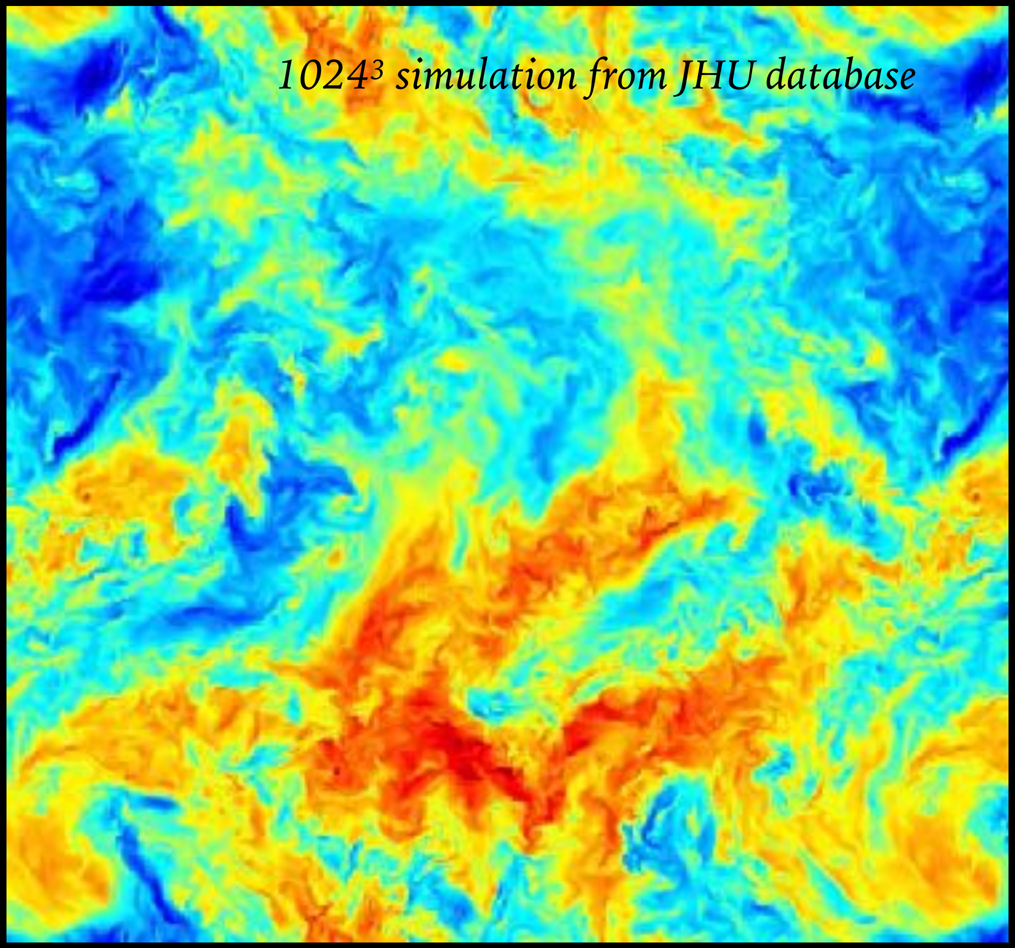
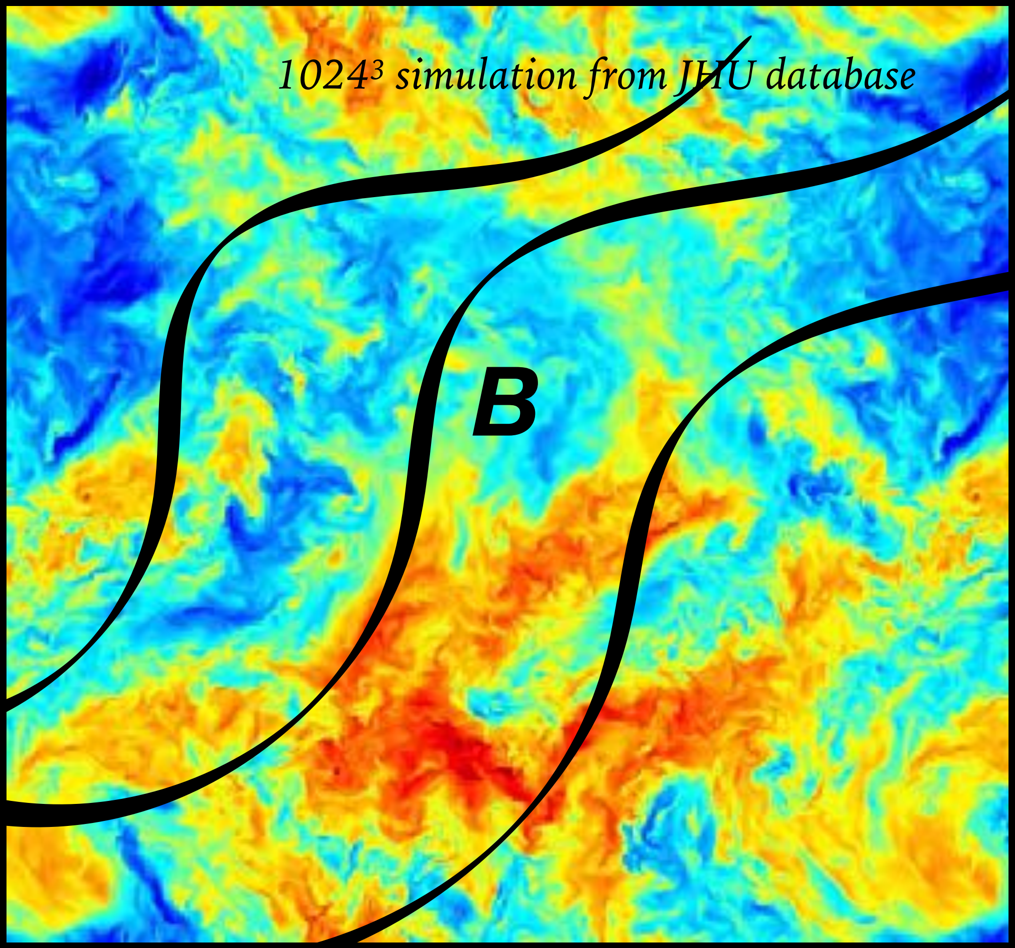


Large-scale dynamo

- Thought experiment: given some smaller-scale turbulence



will it spontaneously generate large-scale magnetic fields?

$$\partial_t \langle \boldsymbol{B} \rangle = \nabla \times (\langle \boldsymbol{u} \rangle \times \langle \boldsymbol{B} \rangle) + \nabla \times \langle \tilde{\boldsymbol{u}} \times \tilde{\boldsymbol{B}} \rangle$$

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Small-scale fluctuations feed back on large scales

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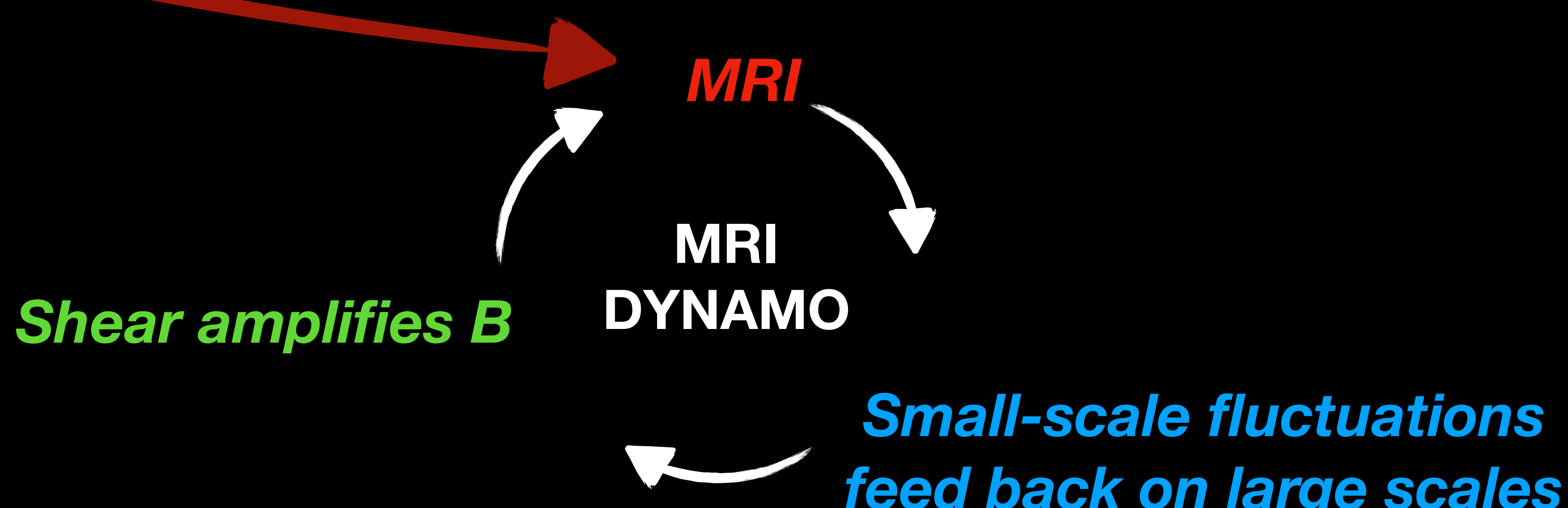

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MRI

MRI DYNAMO

Shear amplifies B

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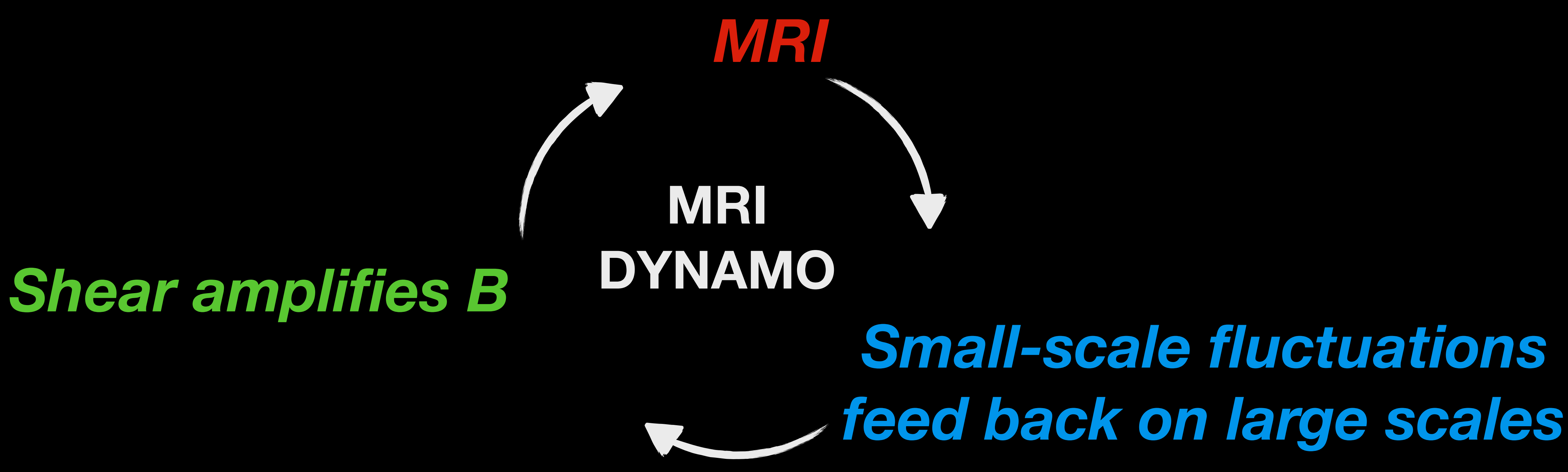

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- Magnetic shear-current effect
- Statistical simulation of the dynamo

Magnetic shear-current effect

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- Standard approach to dynamo has been kinematic:

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"$\boldsymbol{\alpha}$-effect" requires symmetry breaking

Magnetic shear-current effect

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"α-effect" requires symmetry breaking

- *MRI satisfies neither of these requirements*

Magnetic shear-current effect

Magnetic shear-current effect

velocity shear flow

Magnetic shear-current effect

velocity shear flow + **small-scale $\tilde{B}$**

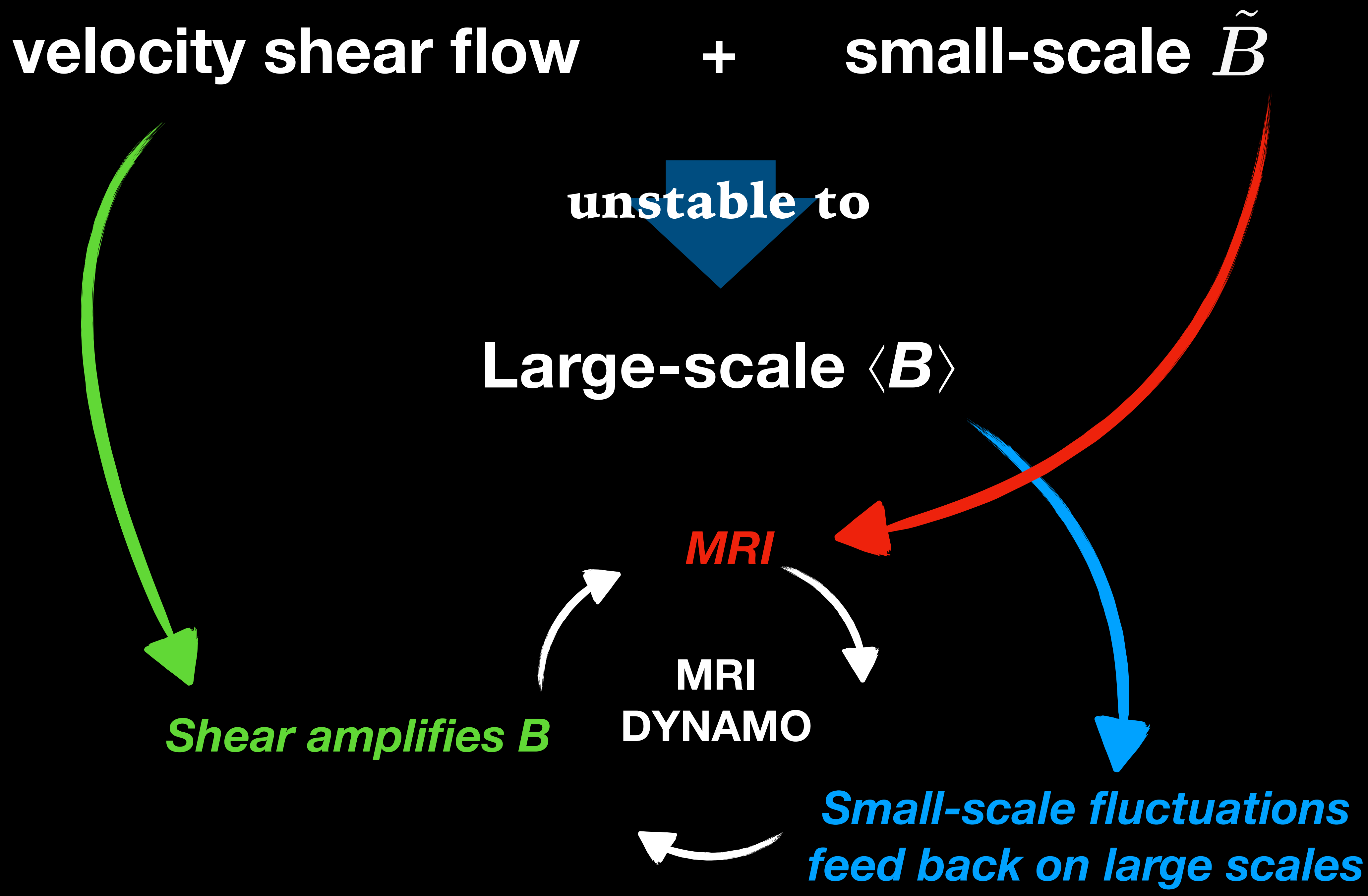
Magnetic shear-current effect

velocity shear flow + **small-scale $\tilde{B}$**

unstable to

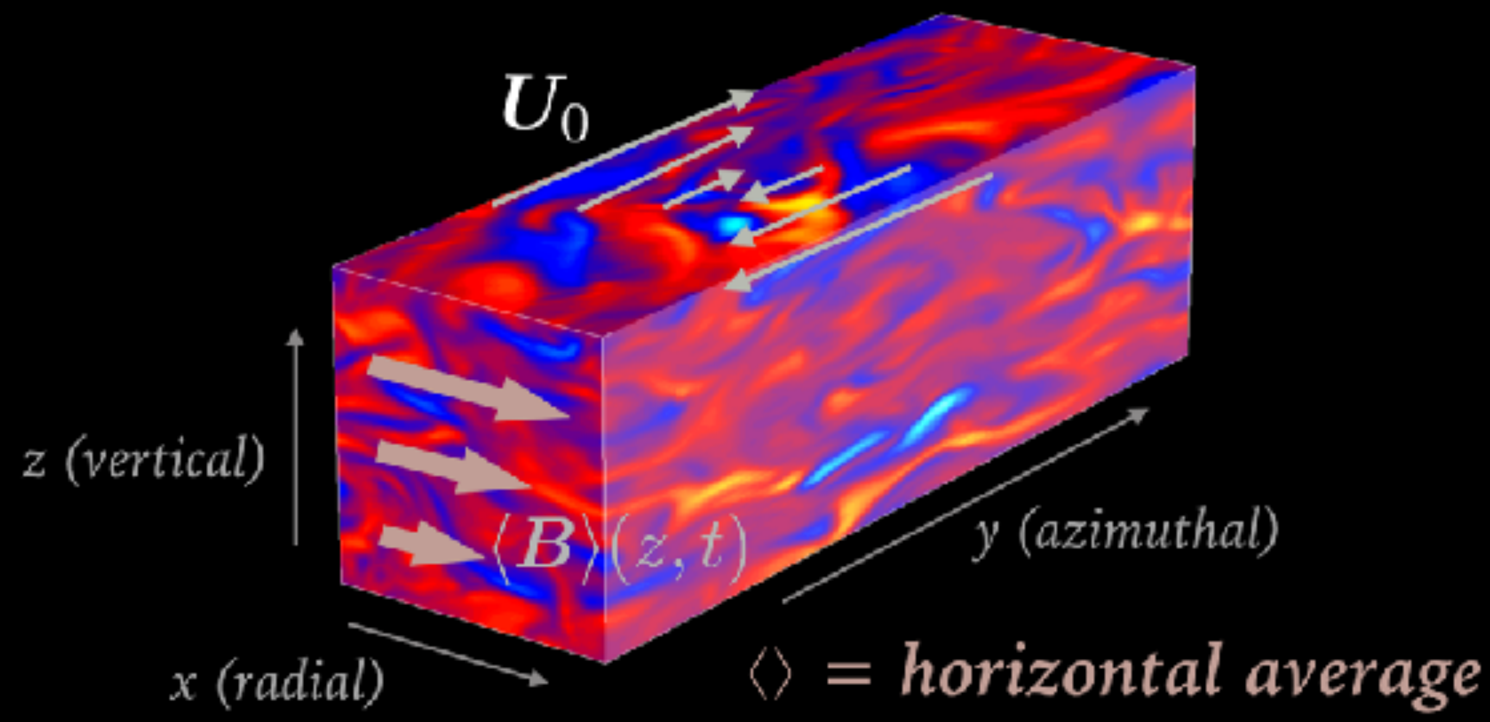
Large-scale $\langle \boldsymbol{B} \rangle$

Magnetic shear-current effect



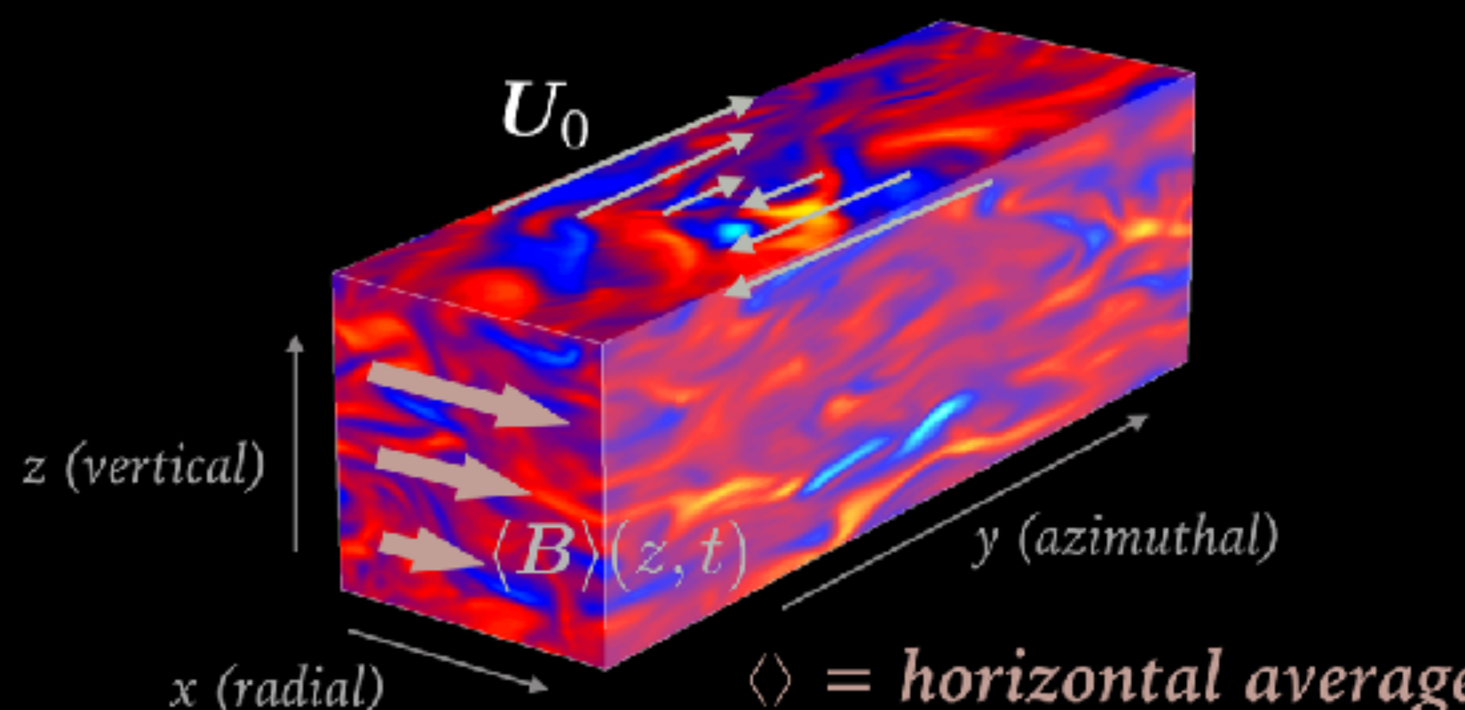
Magnetic shear-current effect

$\langle B_x \rangle$



Magnetic shear-current effect

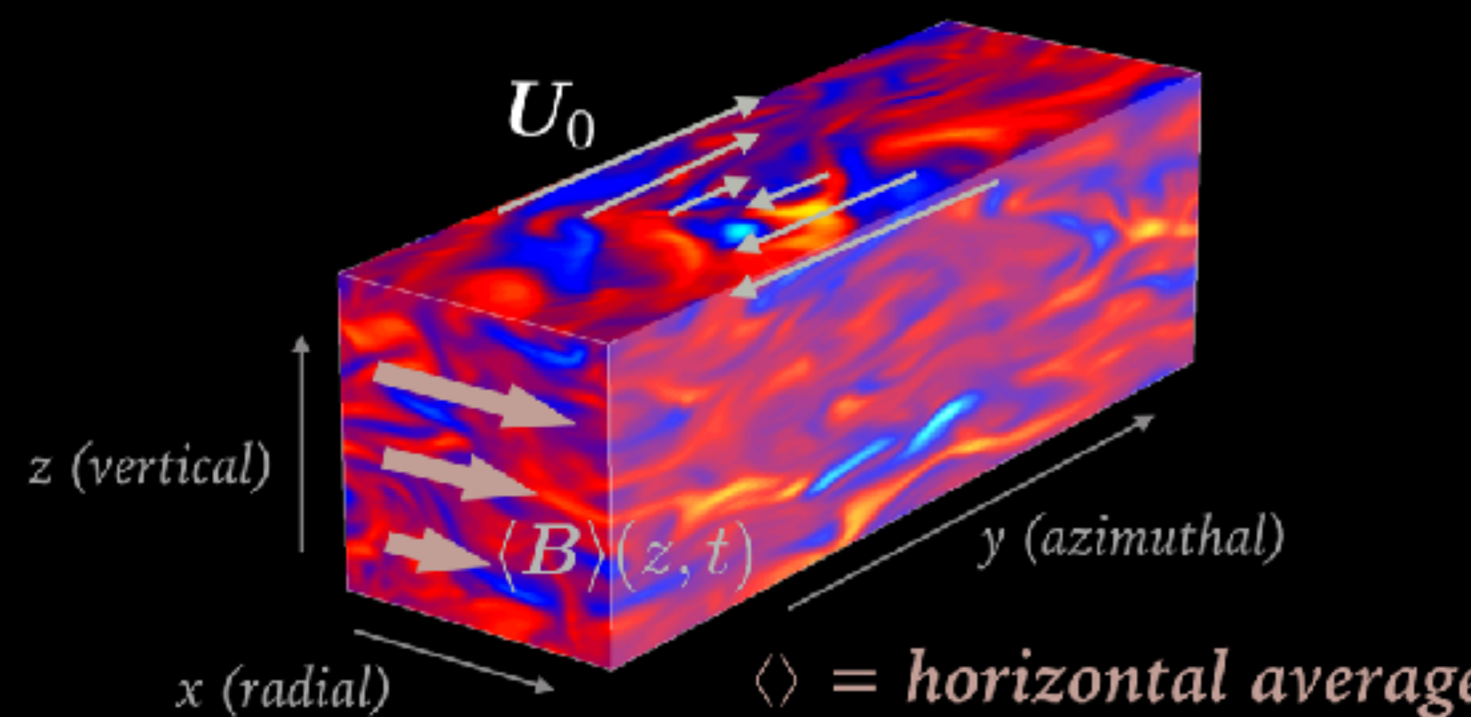
$$\langle B_x \rangle \xrightarrow{\textit{Shear}} \langle B_y \rangle$$



Magnetic shear-current effect

$$\langle B_x \rangle \xrightarrow{\textit{Shear}} \langle B_y \rangle$$

$$\mathcal{E}_y = \beta_{yx} \partial_z \langle B_y \rangle + \ldots$$



Magnetic shear-current effect

Shear

Nonzero due to magnetic fluctuations

$\langle B_x \rangle \xrightarrow{\text{Shear}} \langle B_y \rangle$

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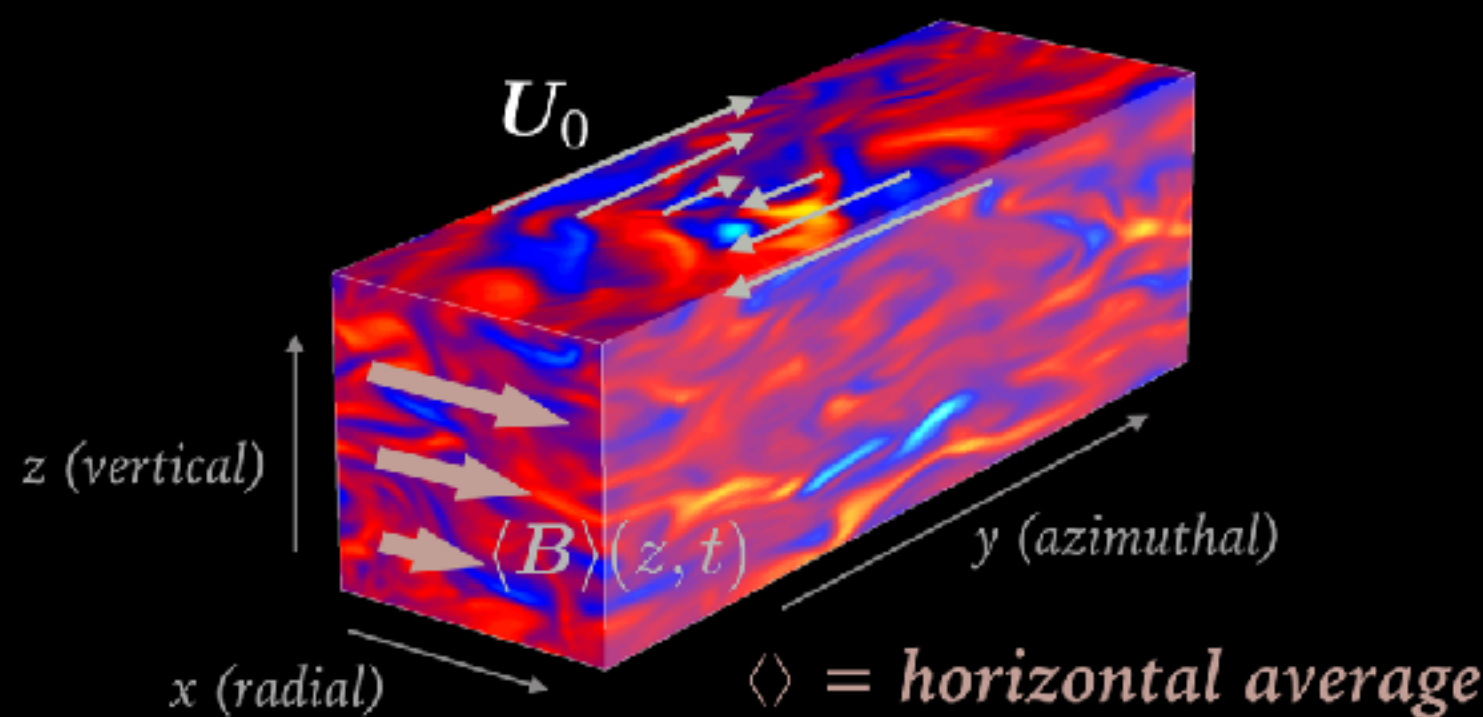

Magnetic shear-current effect

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$$\langle B_x \rangle \qquad \langle B_y \rangle$$

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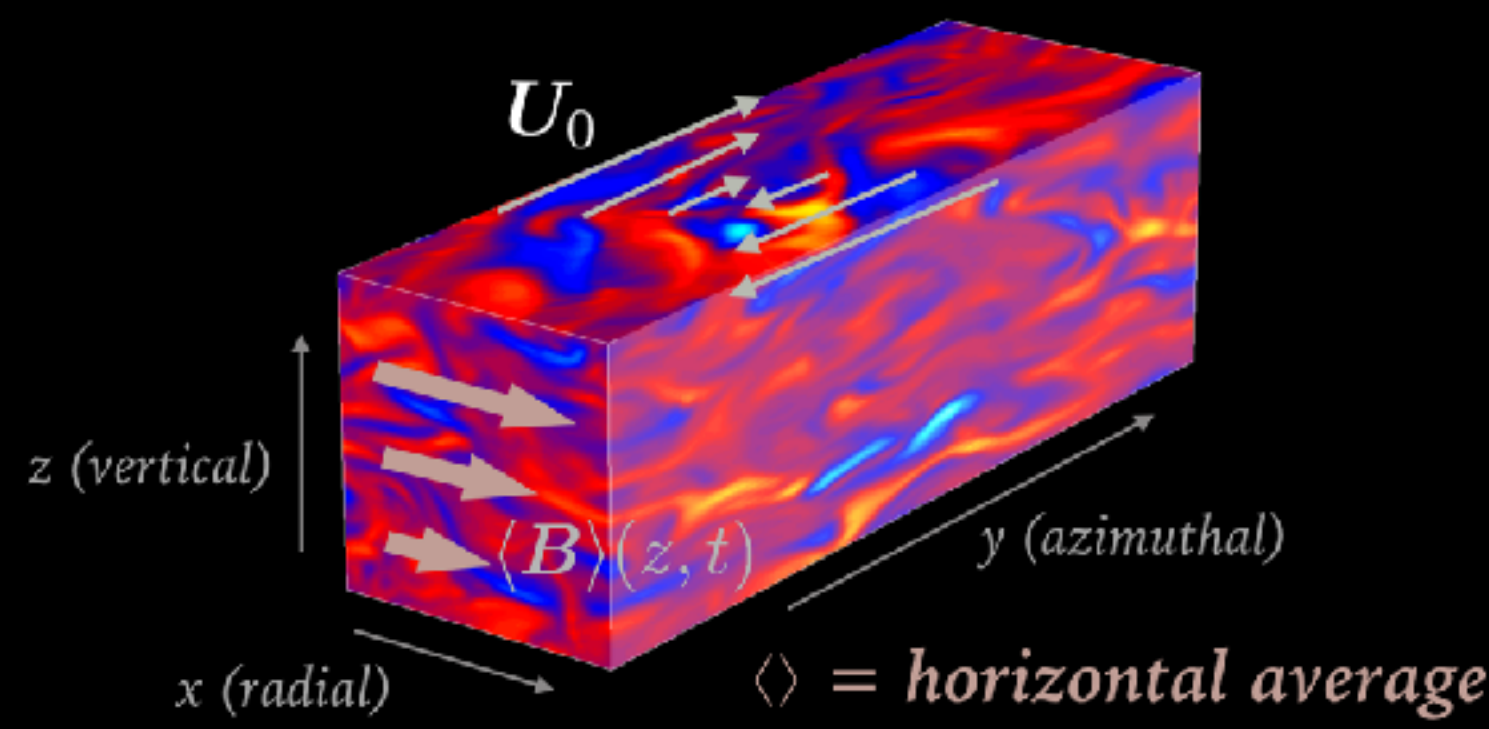


Squire & Bhattacharjee JPP (2016)

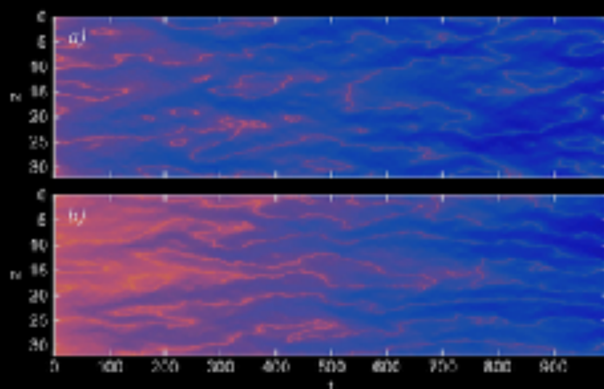
Use several methods to study $\mathcal{E}(\langle B\rangle_y)$
Each agree that dynamo can work

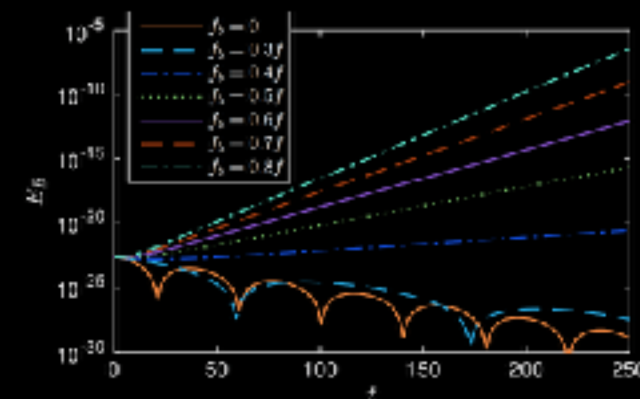
Low Rm quasi-linear and statistical simulation

Squire & Bhattacharjee ApJ (2015)

$$C = \begin{pmatrix} \langle uu^\dagger\rangle & \langle ub^\dagger\rangle \\ \langle bu^\dagger\rangle & \langle bb^\dagger\rangle \end{pmatrix}.$$

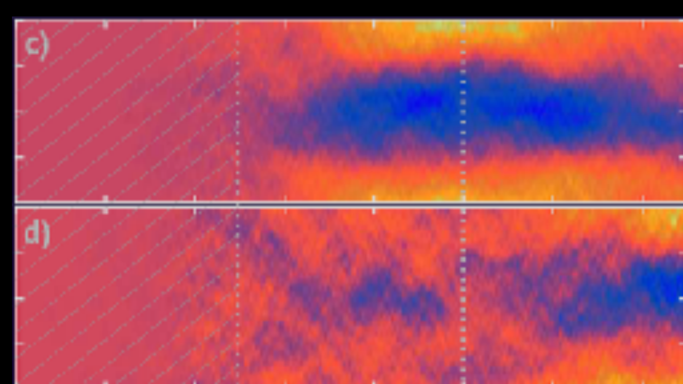
$$\partial_t C = \mathcal{A}C + C\mathcal{A}^\dagger + \mathcal{Q},$$

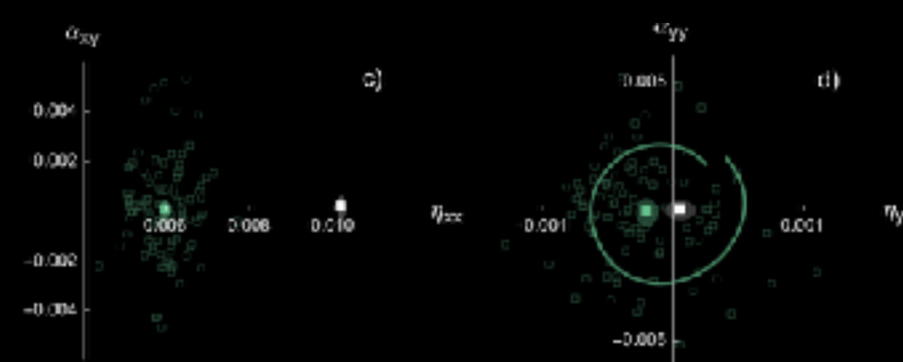




Nonlinear simulations

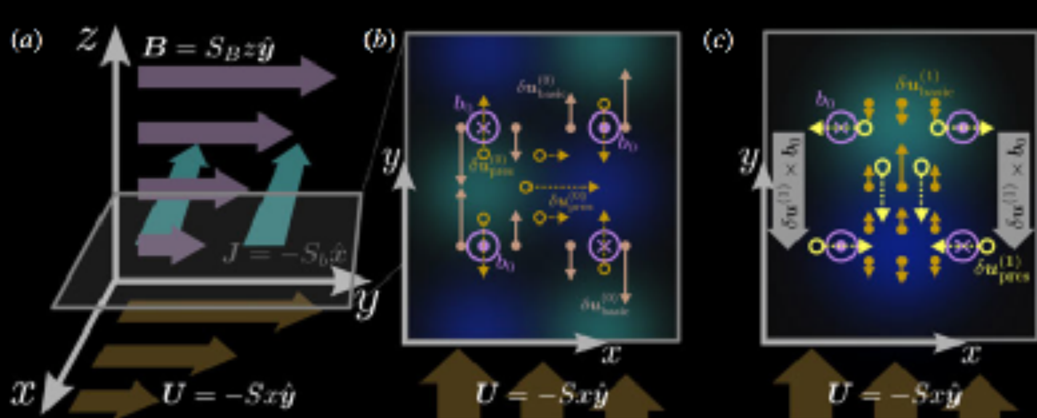
Squire & Bhattacharjee PRL (2015)



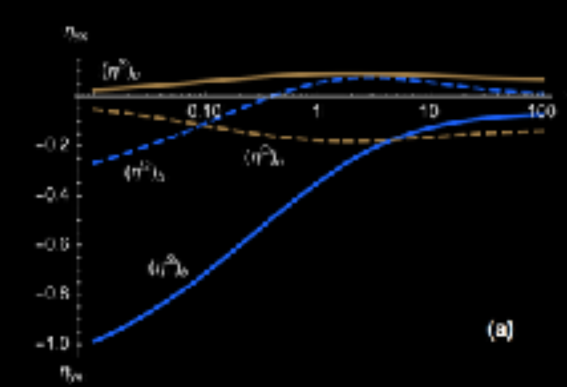


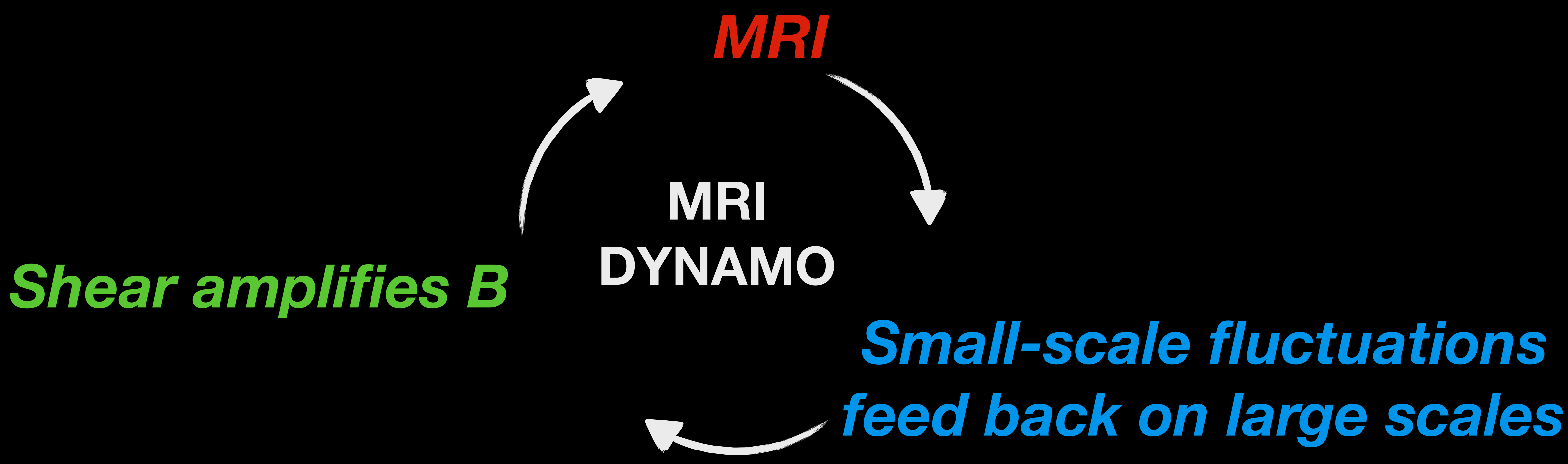
Analytic calculations

Squire & Bhattacharjee PRE (2015)



$$\begin{aligned}\mathcal{E} = &-\alpha_H^{(0)} B - \alpha_H^{(D)} D_{ij} B_j - \gamma_H^{(\Omega)}\Omega\times B - \gamma_H^{(W)} W\times B\\ &-\alpha_1^{(\Omega)}(\hat{g}\cdot\Omega)B - \alpha_2^{(\Omega)}[(\hat{g}\cdot B)\Omega + (B\cdot\Omega)\hat{g}]\\ &-\alpha_1^{(W)}(\hat{g}\cdot W)B - \alpha_2^{(W)}[(\hat{g}\cdot B)W + (B\cdot W)\hat{g}]\\ &-\alpha^{(D)}(\varepsilon_{ilm}D_{lj}\hat{g}_m + \varepsilon_{jlm}D_{il}\hat{g}_m)B_j\\ &-(\gamma^{(0)} + \gamma^{(\Omega)}\hat{g}\times\Omega + \gamma^{(W)}\hat{g}\times W + \gamma^{(D)}D_{ij}\hat{g}_j)\times B\\ &-\beta^{(0)}J - \beta^{(D)}D_{ij}J_j - (\delta^{(W)}W + \delta^{(\Omega)}\Omega)\times J\\ &-(\kappa^{(W)}W + \kappa^{(\Omega)}\Omega)_j(\nabla B)^{(s)}_{ji} - 2\kappa^{(D)}\varepsilon_{ijk}D_{kr}(\nabla B)^{(s)}_{jr}.\end{aligned}$$





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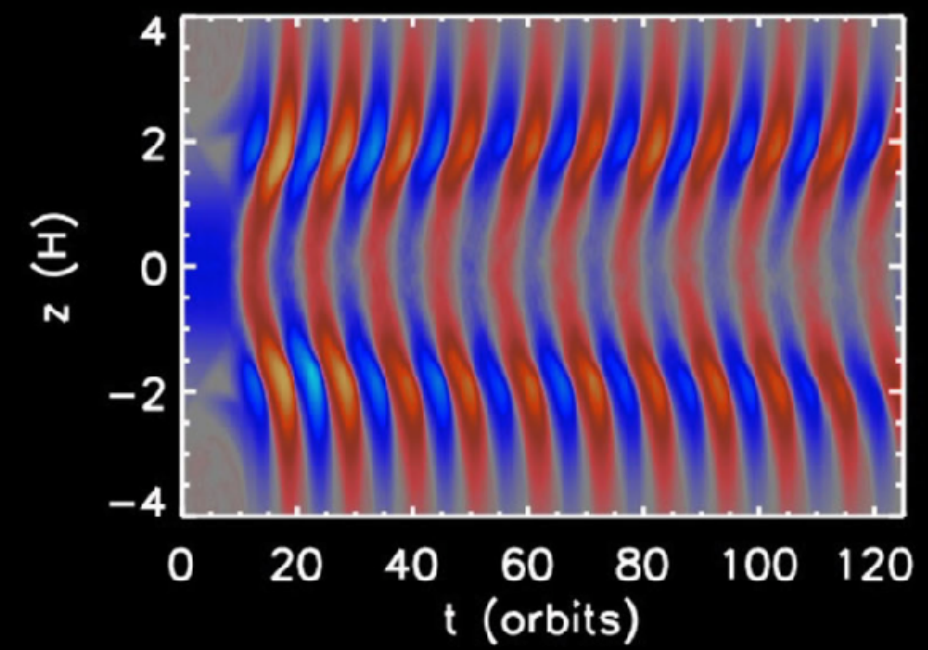
How can we relate abstract dynamo theory to MRI cycles?

Simon et al., MNRAS **422** 2685 (2012)



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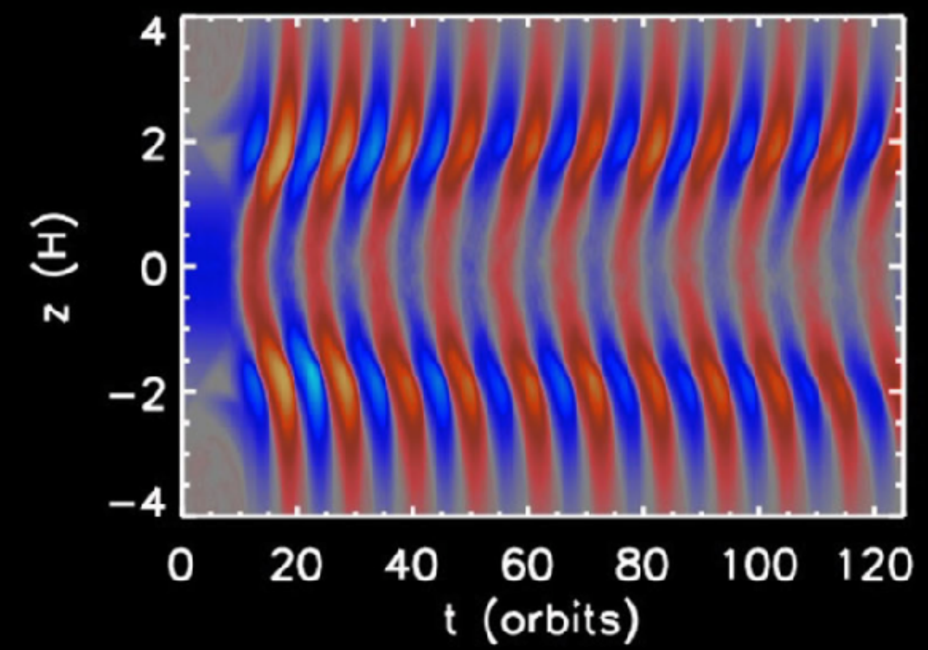

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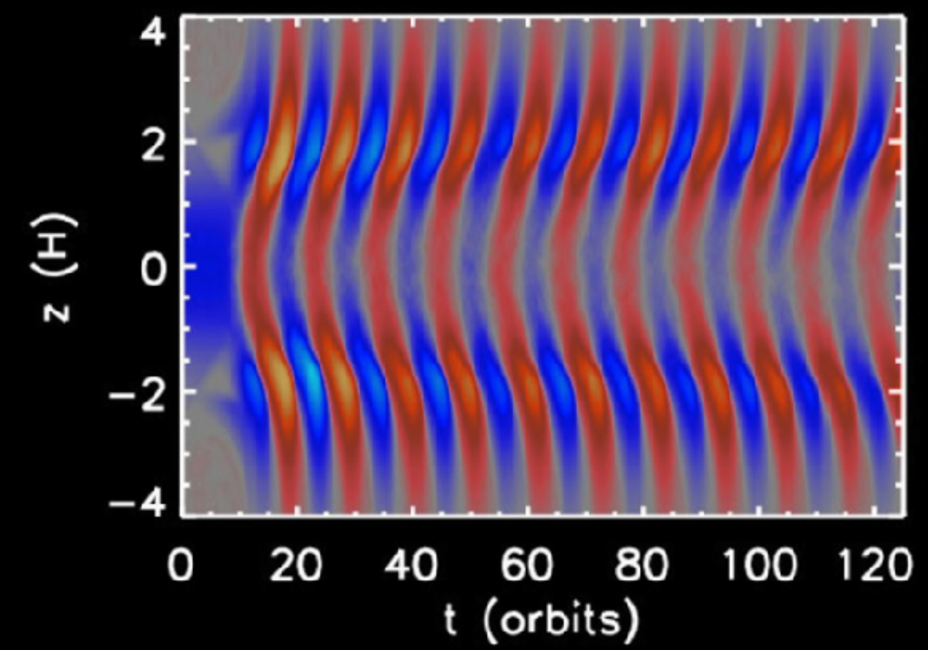

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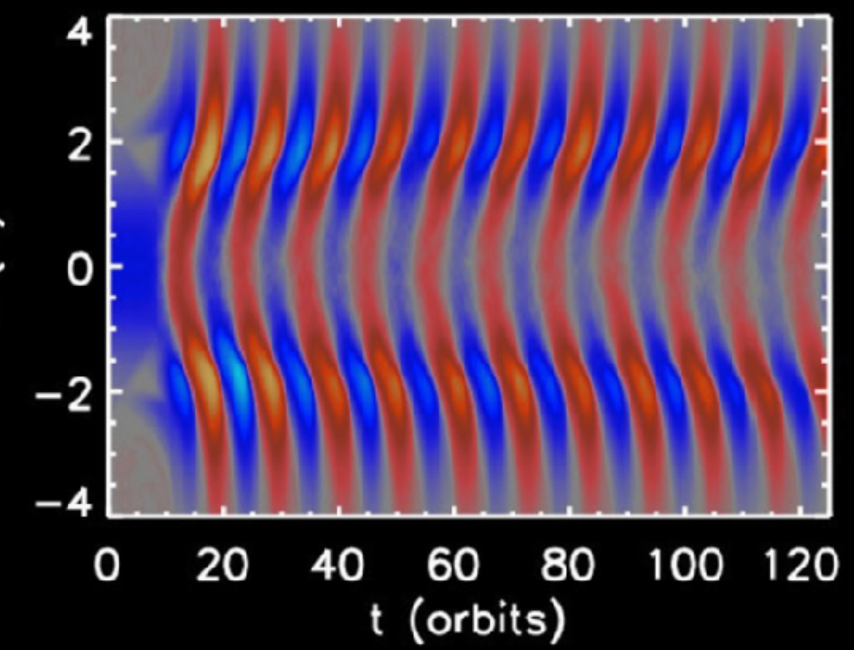

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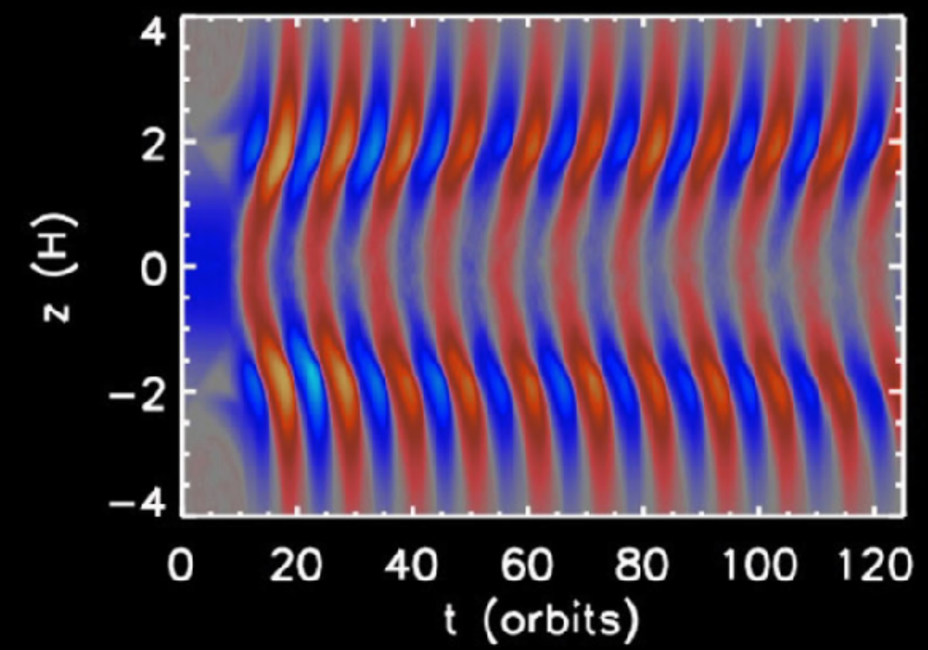

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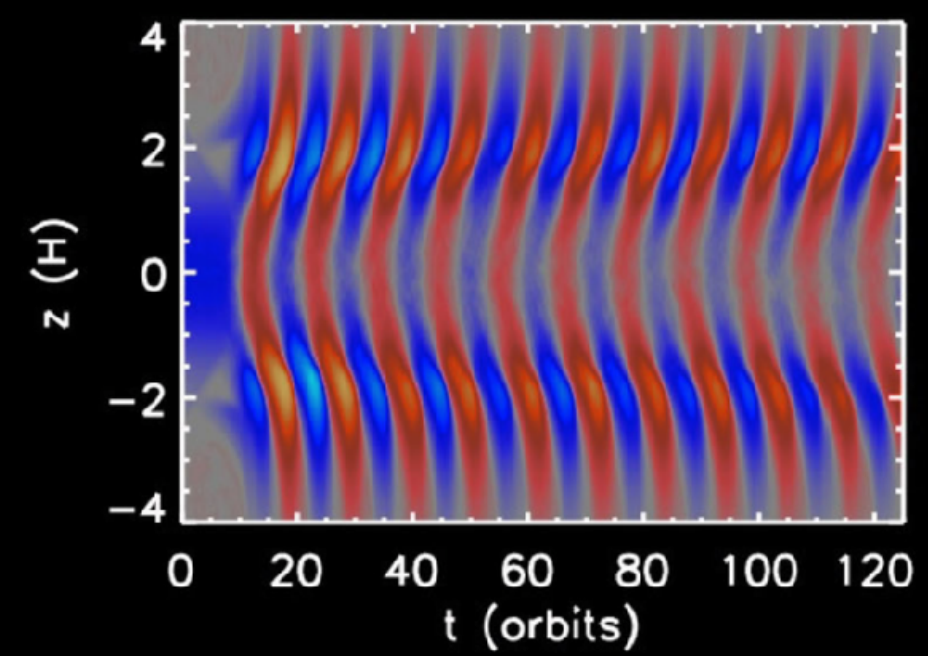

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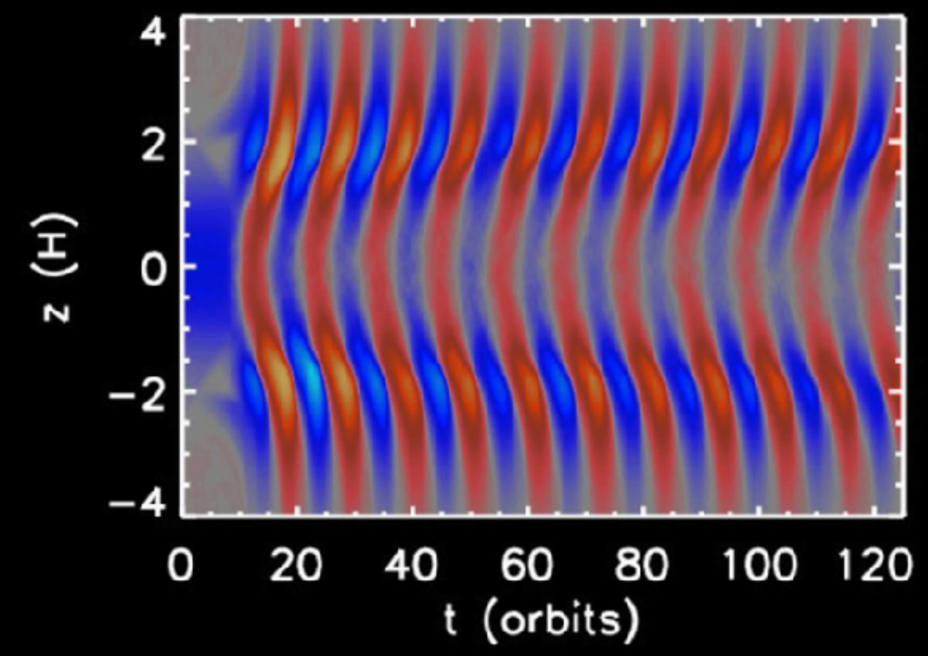

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Approximate equations
Requires forcing

Statistical simulation

IDEA:

Evolve

$$\langle \tilde{u}\tilde{u} \rangle \quad \langle \tilde{u}\tilde{B} \rangle \quad \langle \tilde{B}\tilde{B} \rangle$$

$$\langle B \rangle \quad \langle u \rangle$$

Statistical simulation

IDEA:

Evolve $\langle \tilde{u}\tilde{u} \rangle$ $\langle \tilde{u}\tilde{B} \rangle$ $\langle \tilde{B}\tilde{B} \rangle$

$\langle B \rangle$ $\langle u \rangle$

ADVANTAGE:

Directly study large-scale dynamo, isolate mechanism

Statistical simulation

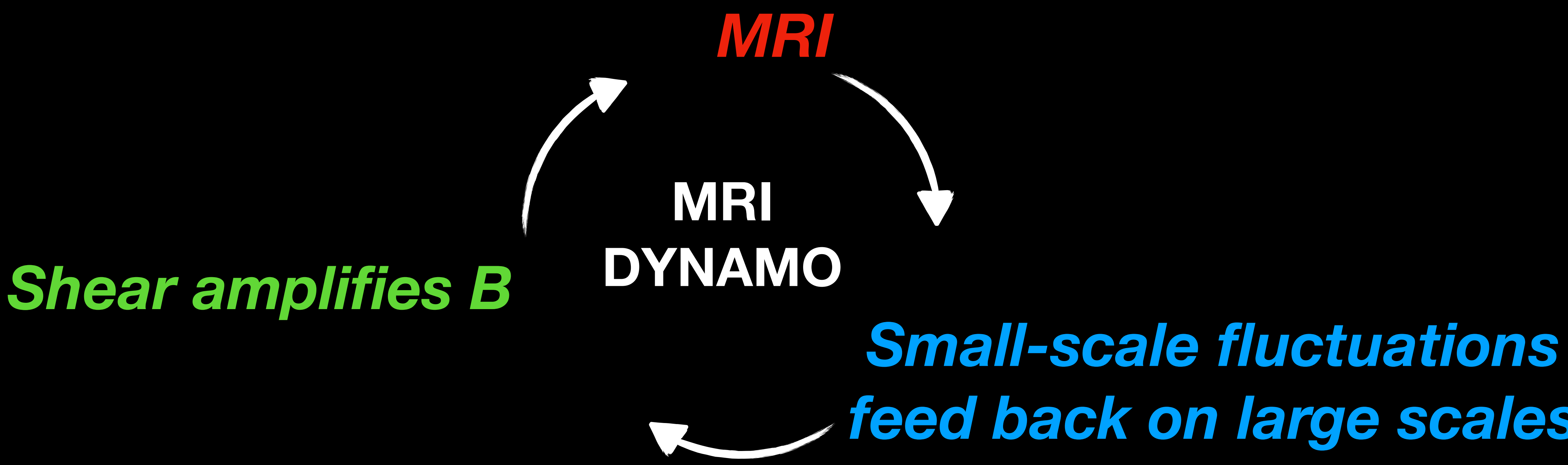
IDEA: **Evolve** $\langle \tilde{u}\tilde{u} \rangle \quad \langle \tilde{u}\tilde{B} \rangle \quad \langle \tilde{B}\tilde{B} \rangle$

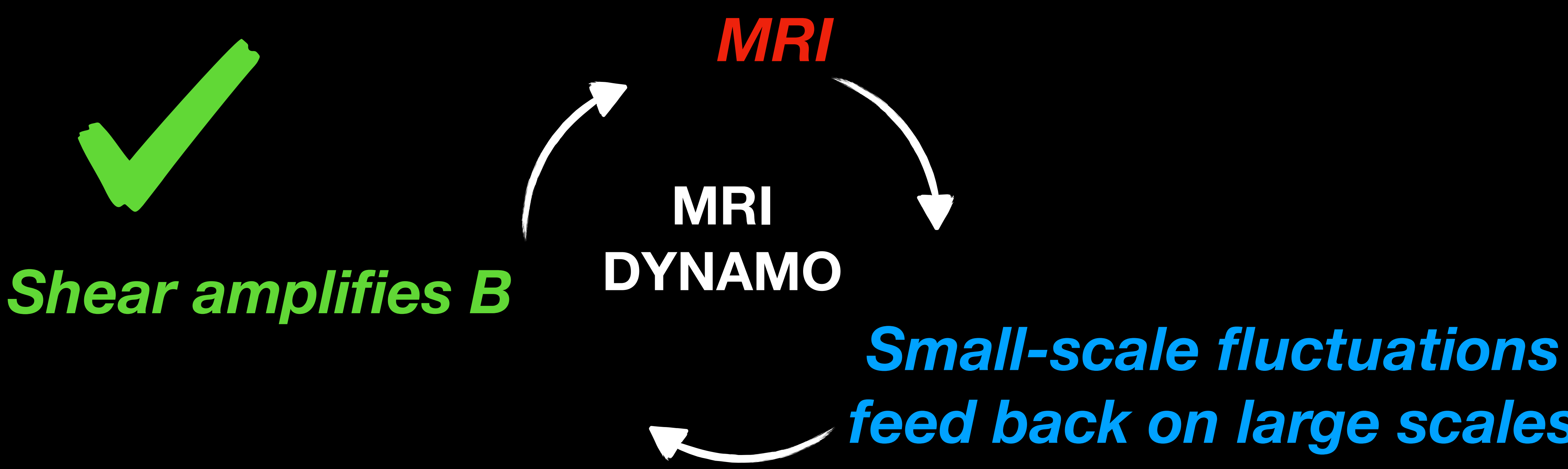
$\langle B \rangle \quad \langle u \rangle$

ADVANTAGE: *Directly study large-scale dynamo, isolate mechanism*

DISADVANTAGE: *Have to use quasi-linear approximation*

Turbulence does not self-sustain


MRI
MRI DYNAMO
Shear amplifies B
Small-scale fluctuations feed back on large scales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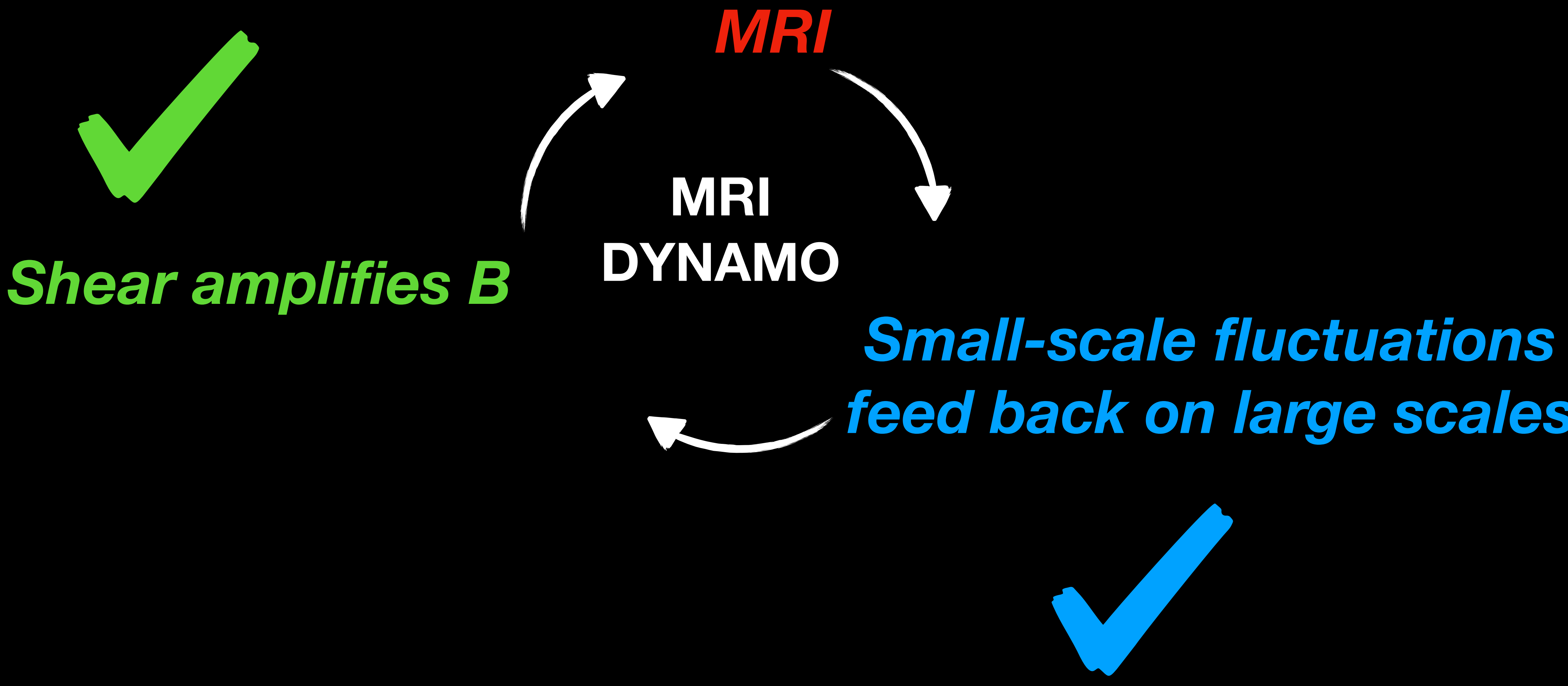
MRI
MRI DYNAMO
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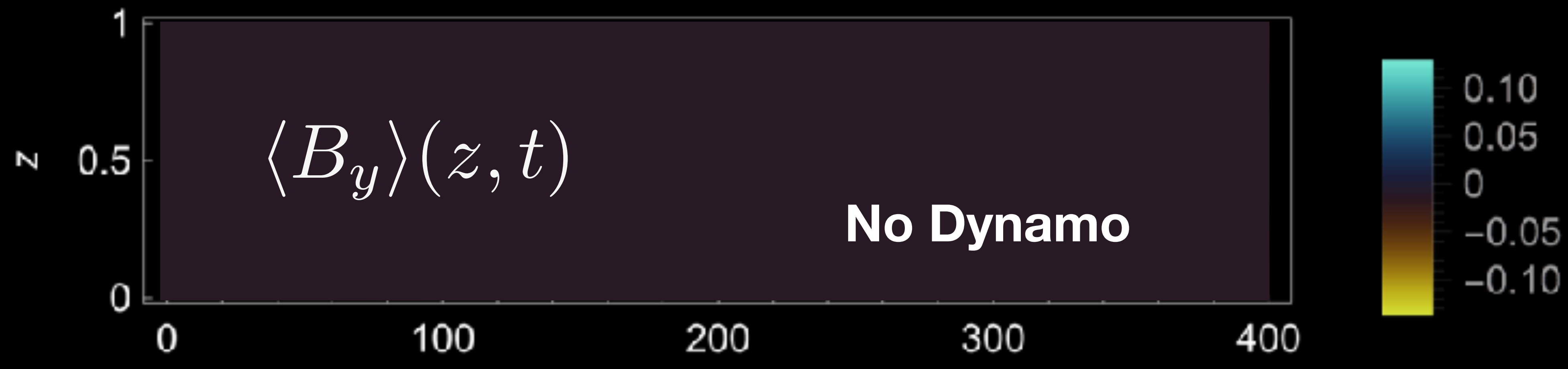
LINEARIZE

MRI

MRI DYNAMO

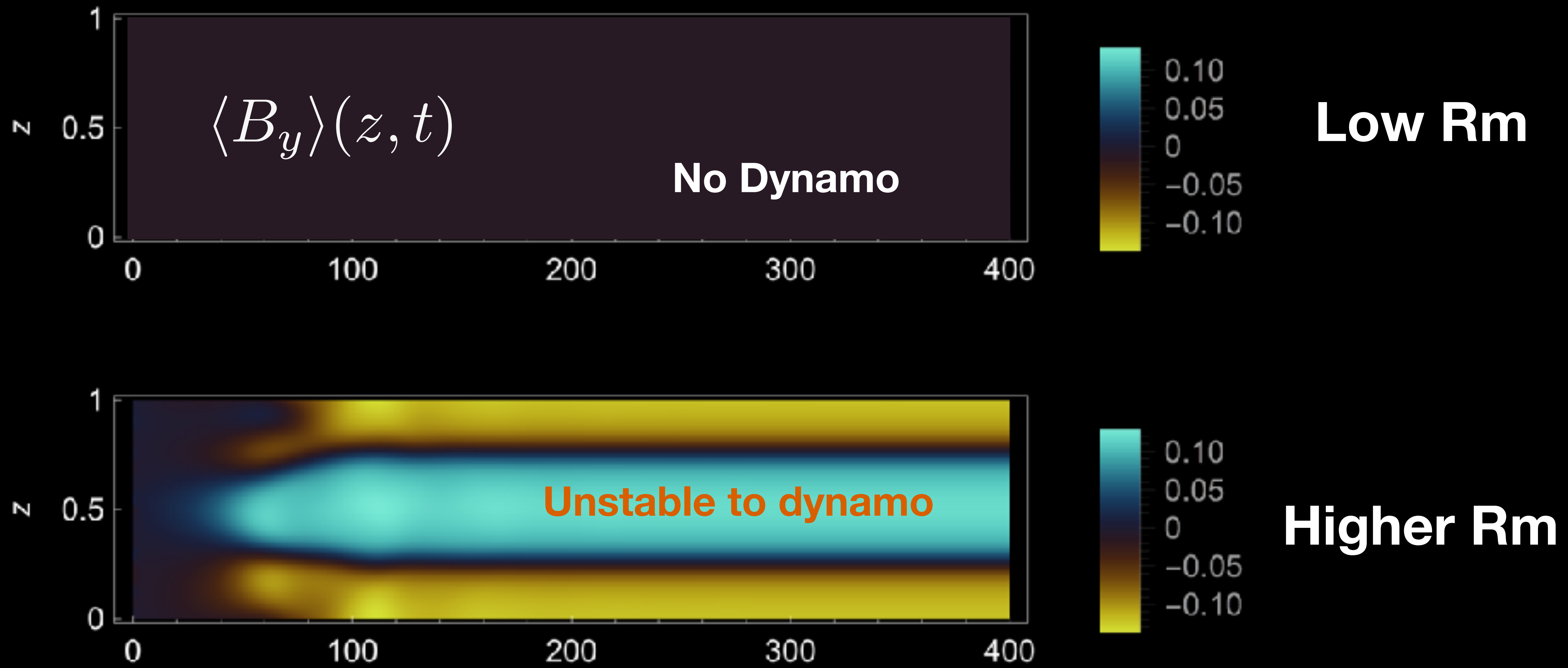
Shear amplifies B

Small-scale fluctuations feed back on large scales



$\langle B_y \rangle (z,t)$
No Dynamo
z
1
0.5
0
0
100
200
300
400
0.10
0.05
0
−0.05
−0.10

Low Rm



$\langle B_y \rangle(z,t)$
No Dynamo
Low Rm
Unstable to dynamo
Higher Rm
z
0
0.5
1
0
100
200
300
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0.10
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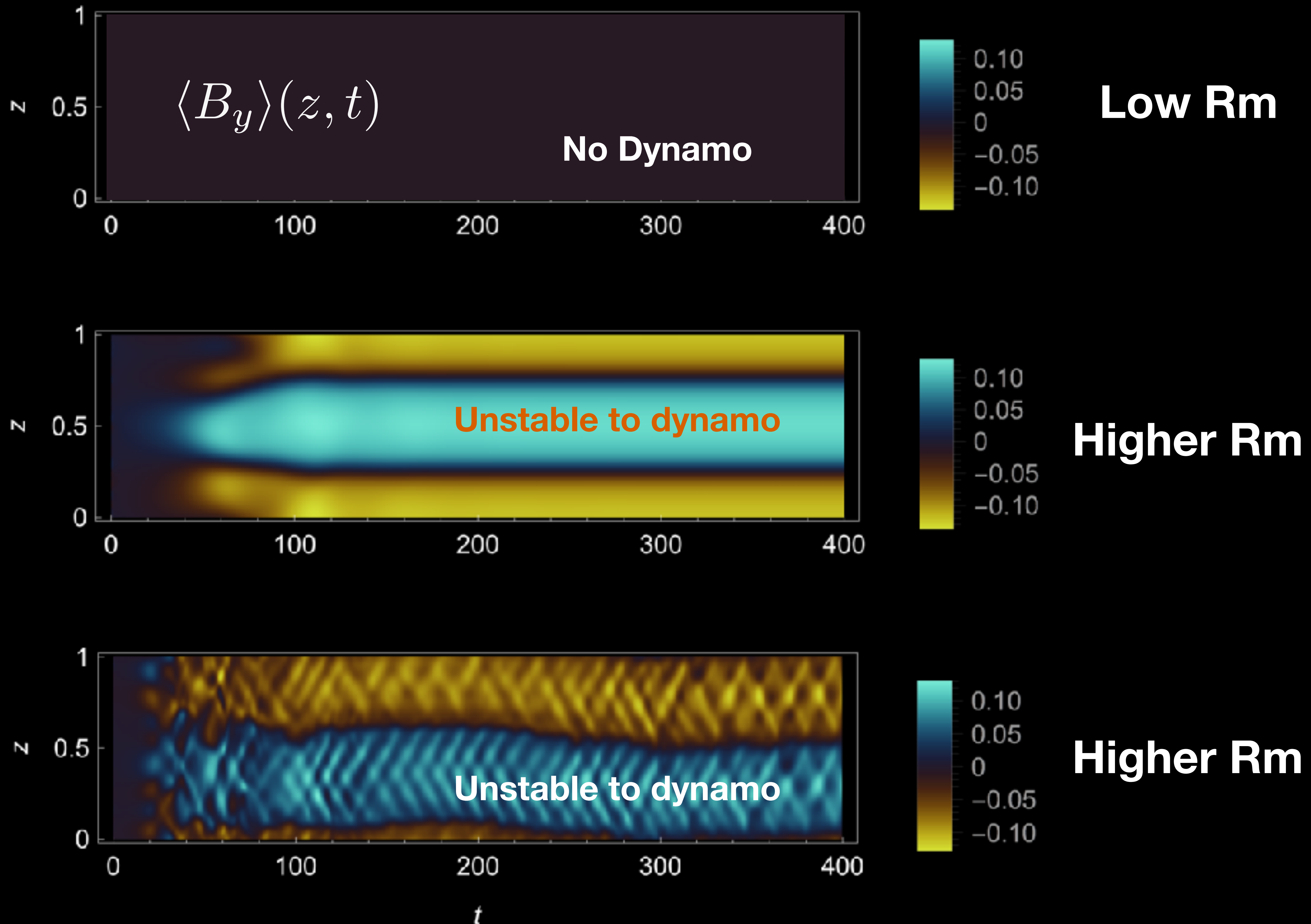

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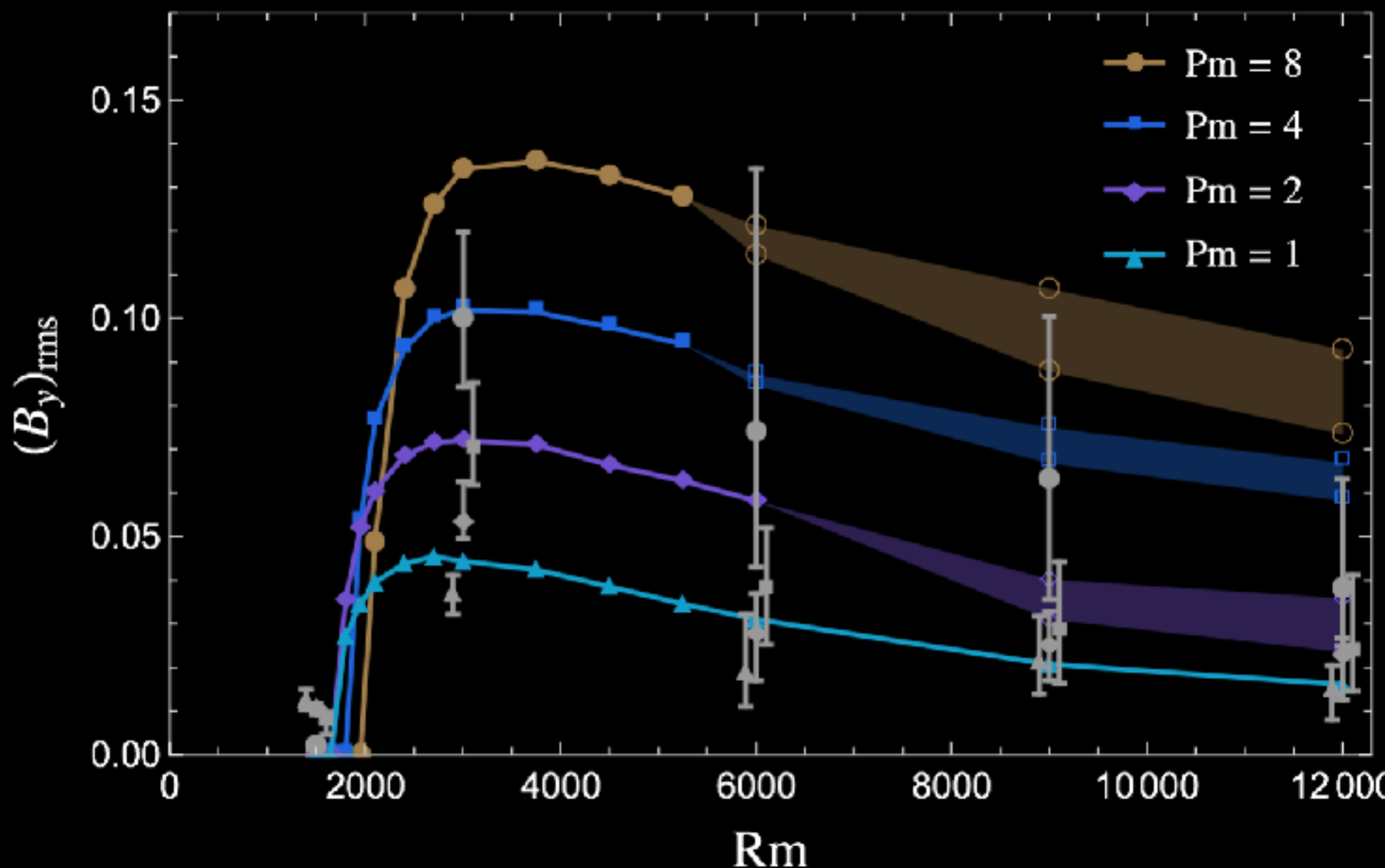
Saturated dynamo depends strongly on Pm



Squire & Bhattacharjee 2015

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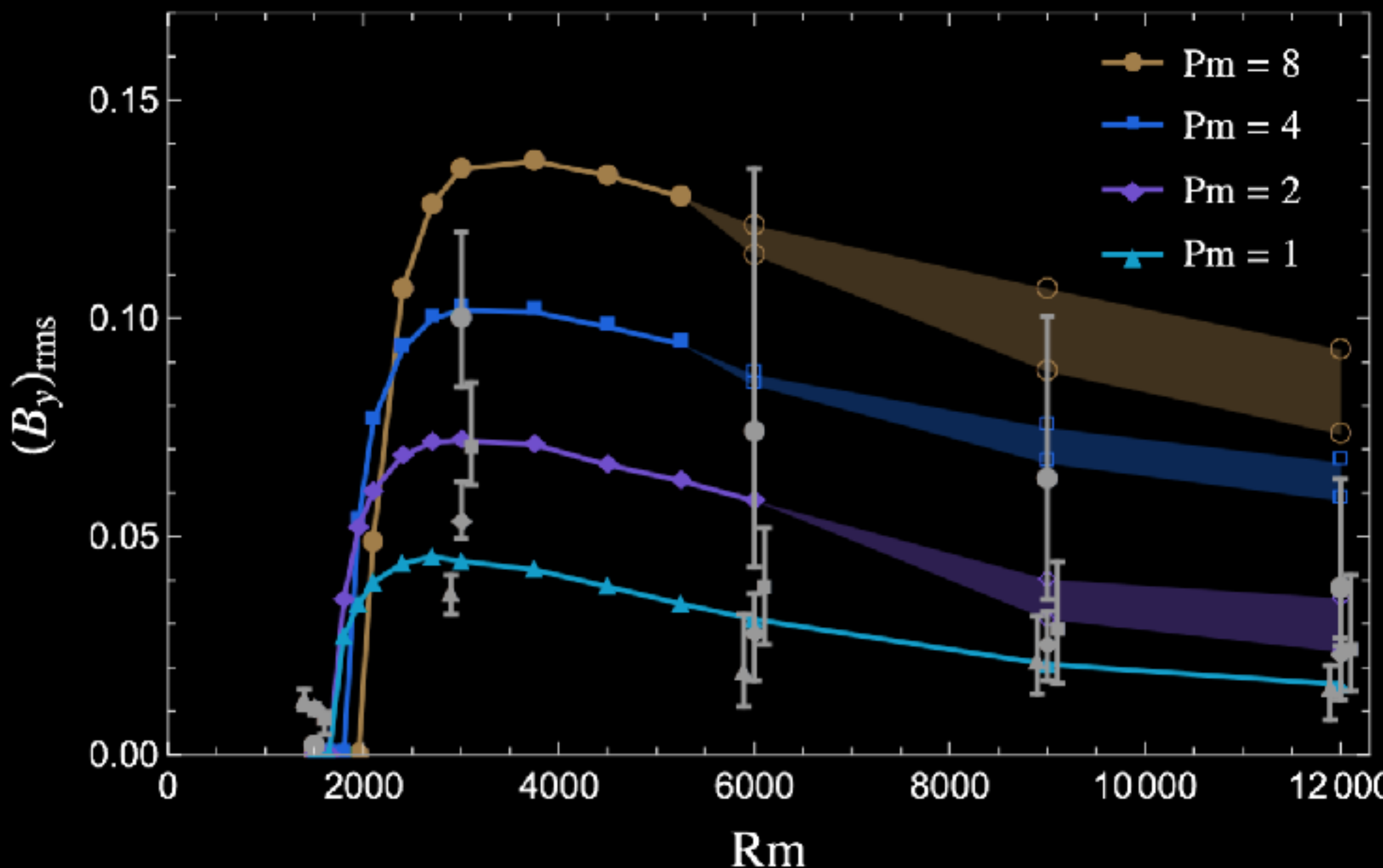
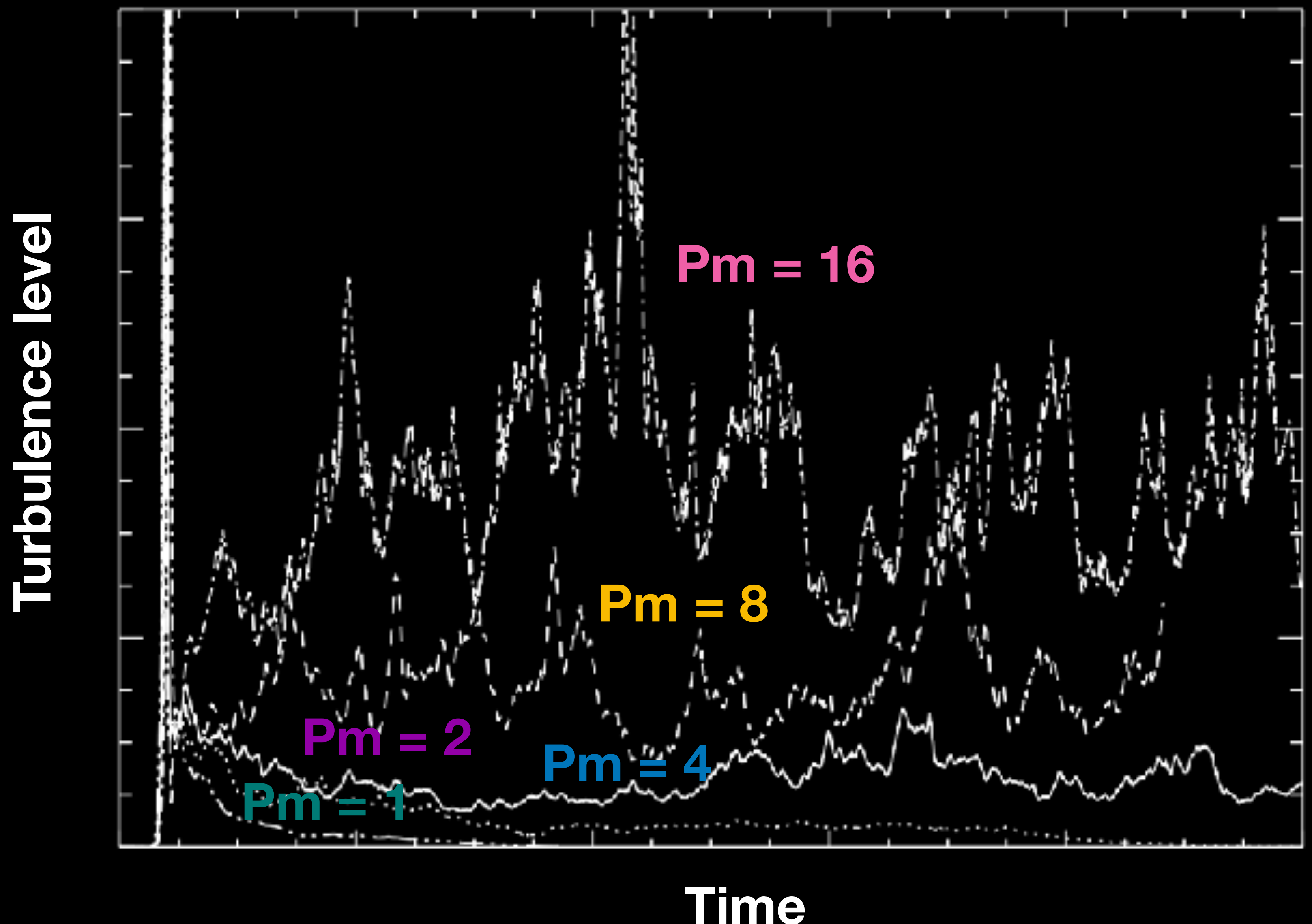


Squire & Bhattacharjee 2015

even though high Pm is *more* dissipative

Just like nonlinear MRI turbulence



Fromang+ 2007b

This tells us

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1. The coherent large-scale dynamo is (at least partially) responsible for the Pm dependence of MRI turbulence:

   Statistical simulation similar to nonlinear MRI turbulence.

   The only possible reason for this is the dynamo.

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   Statistical simulation similar to nonlinear MRI turbulence.

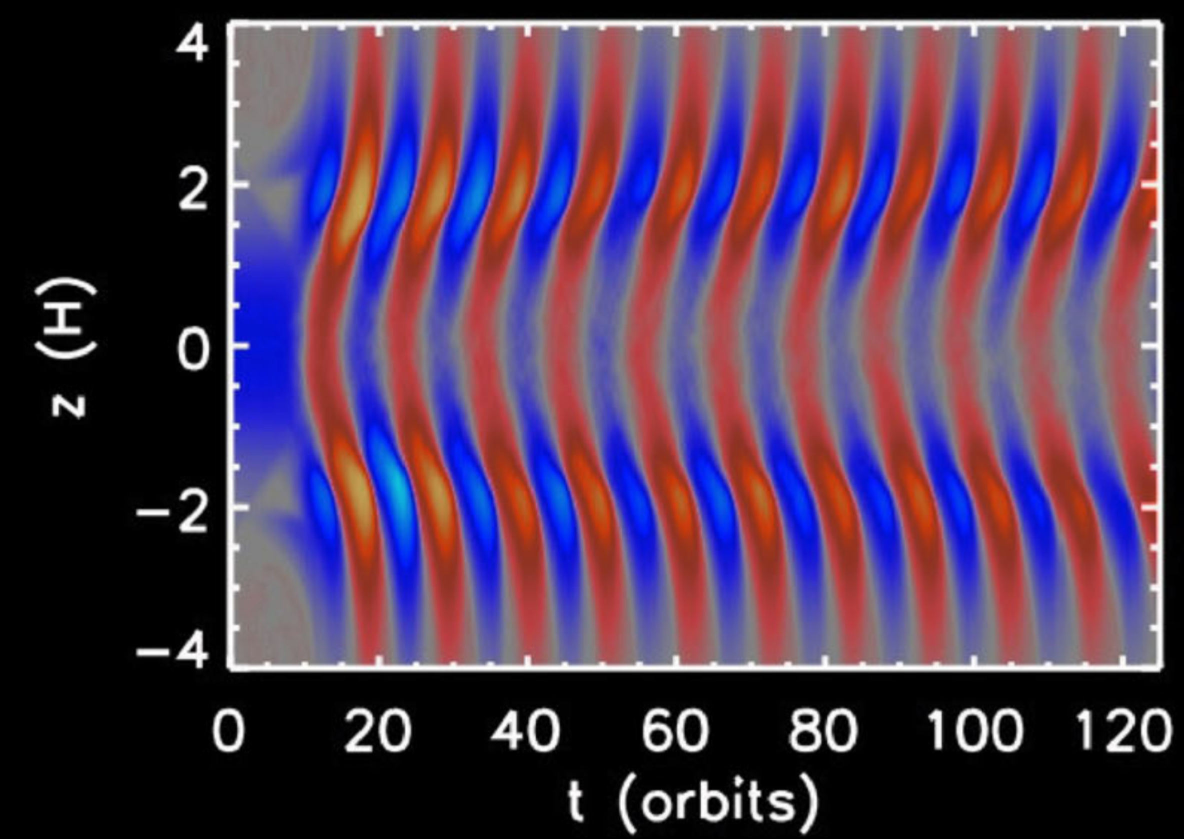
   The only possible reason for this is the dynamo.

2. The dynamo mechanism is the magnetic shear-current effect:

   The kinematic effect cannot drive the observed dynamo.

Simon+ 2012

But still lots of questions:



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- Dynamo saturation

  Related to stabilization by radial MRI

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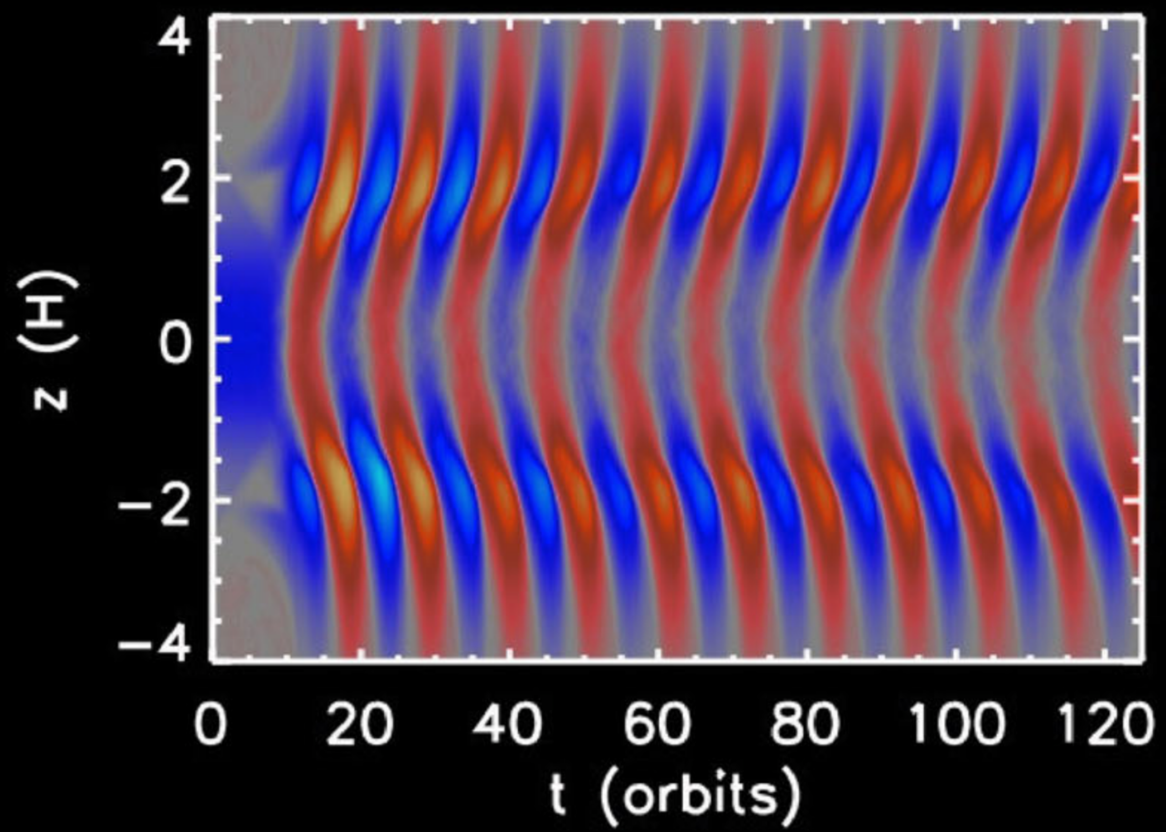

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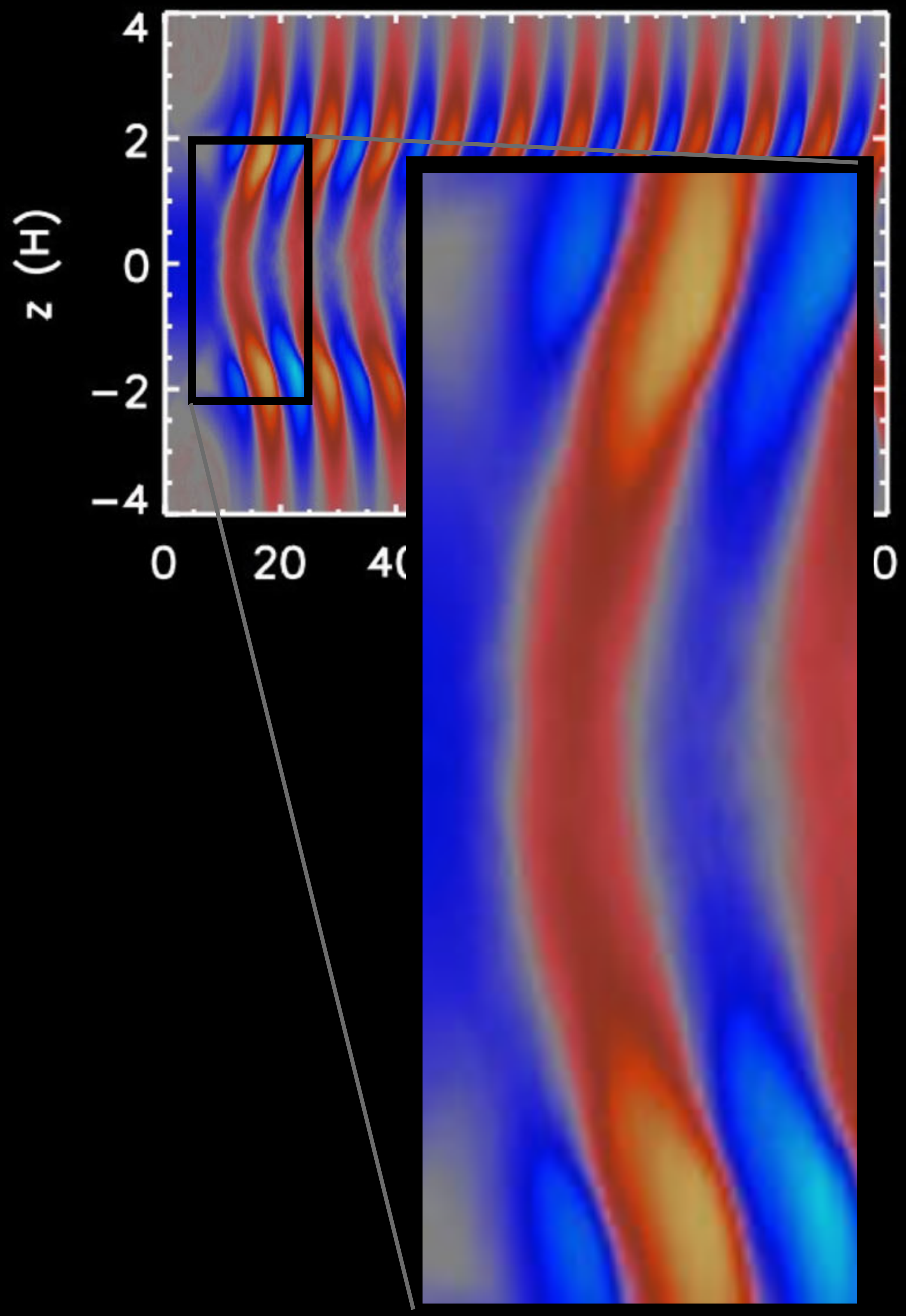

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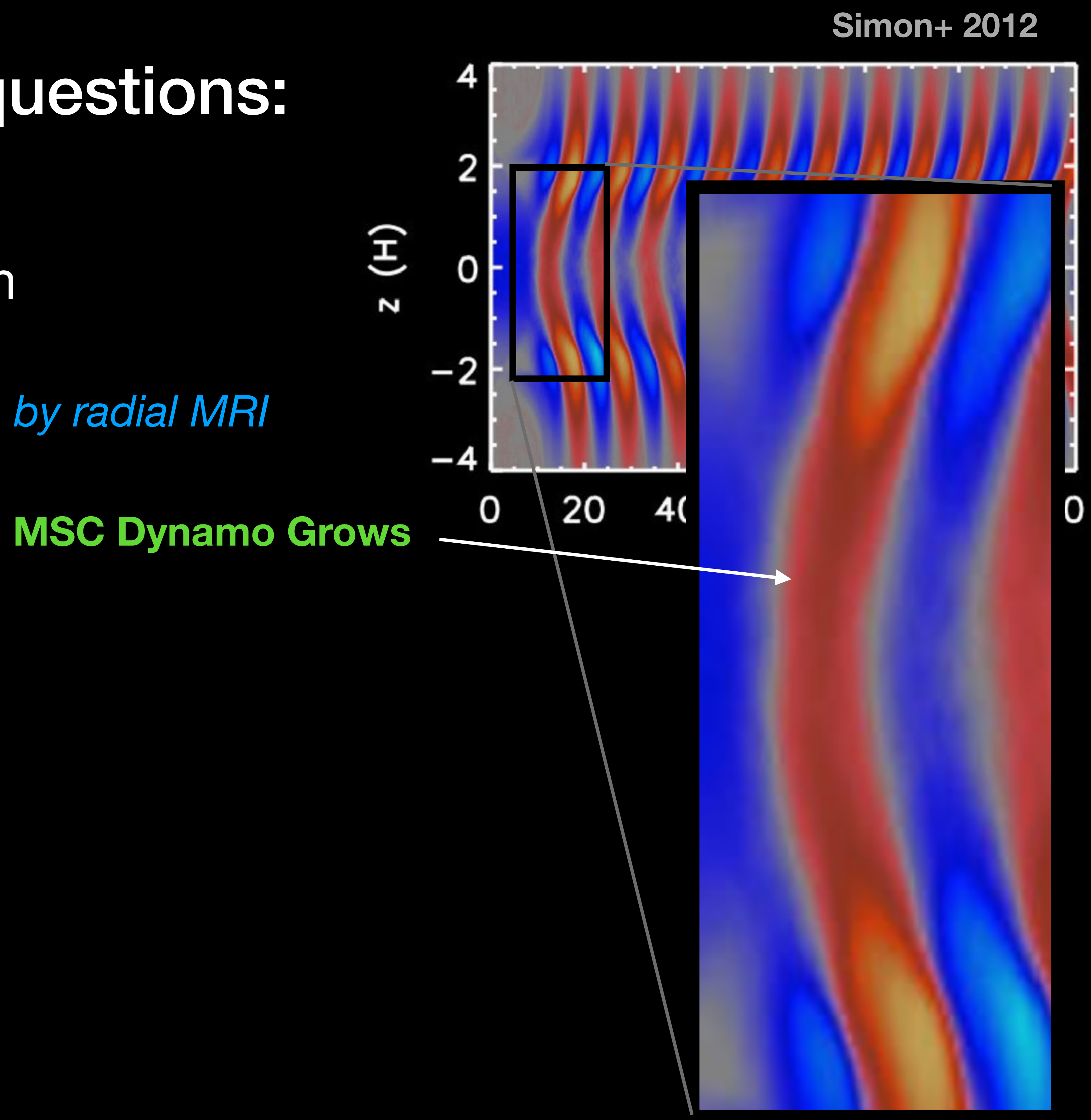

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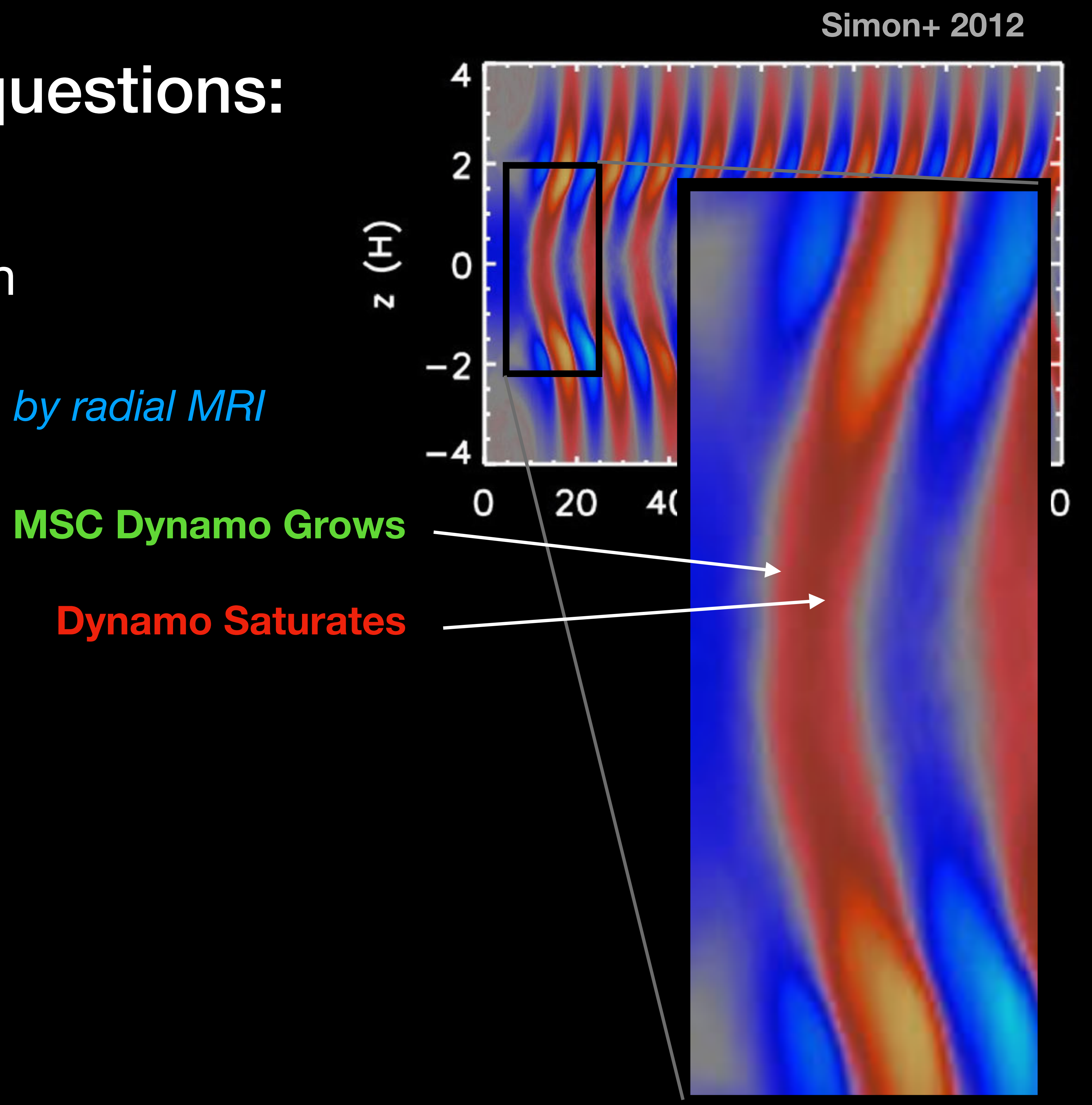

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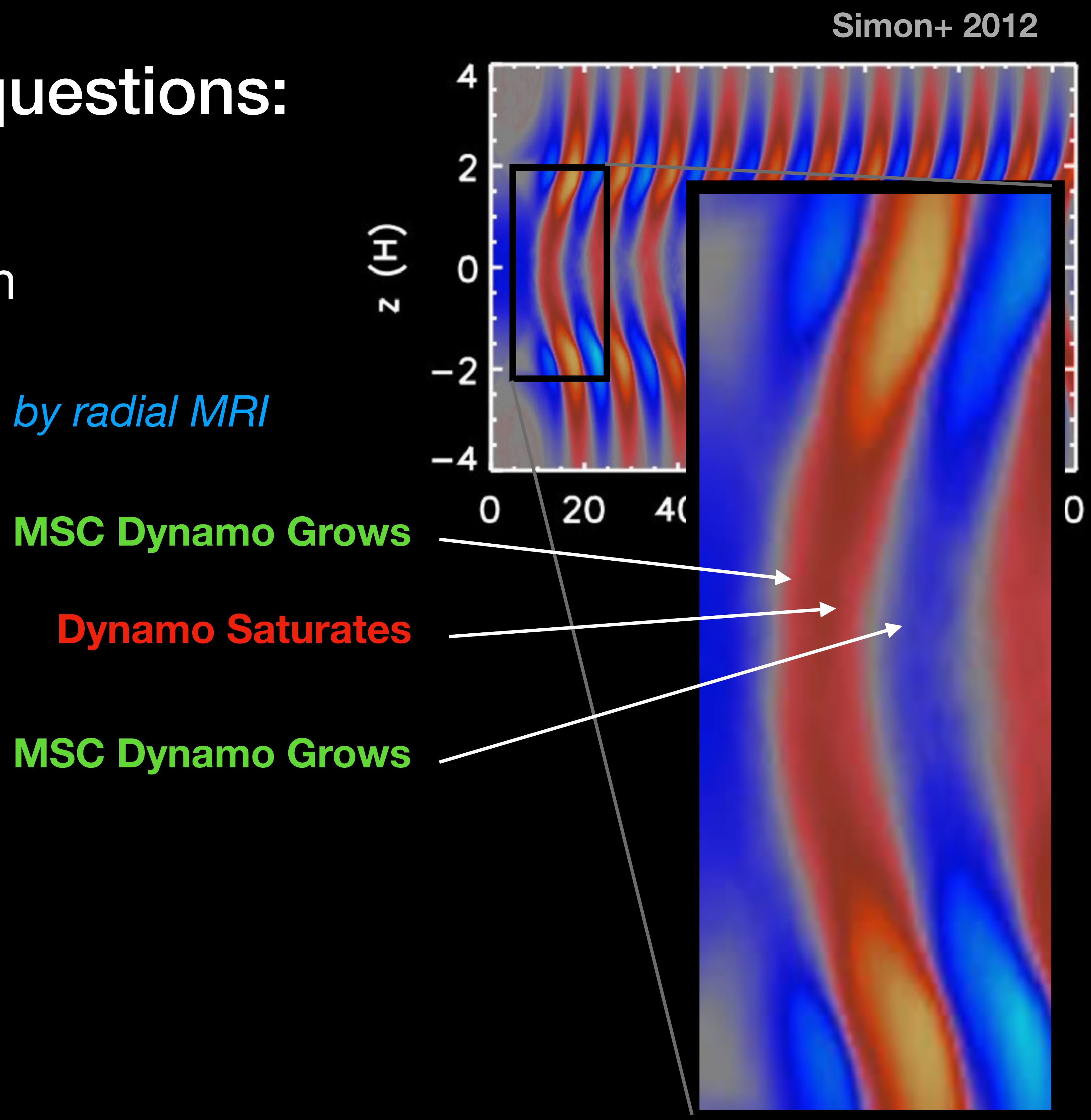

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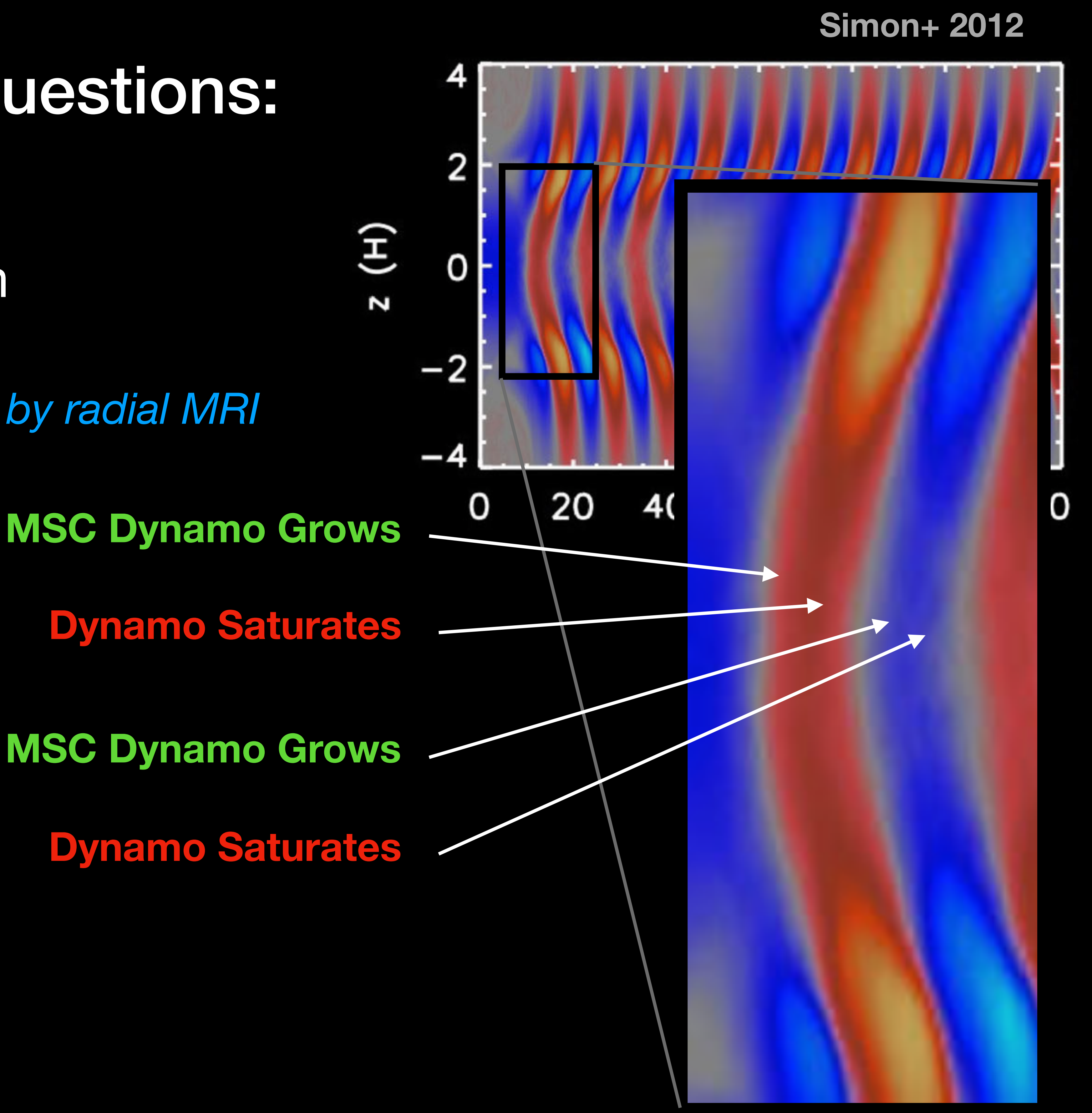

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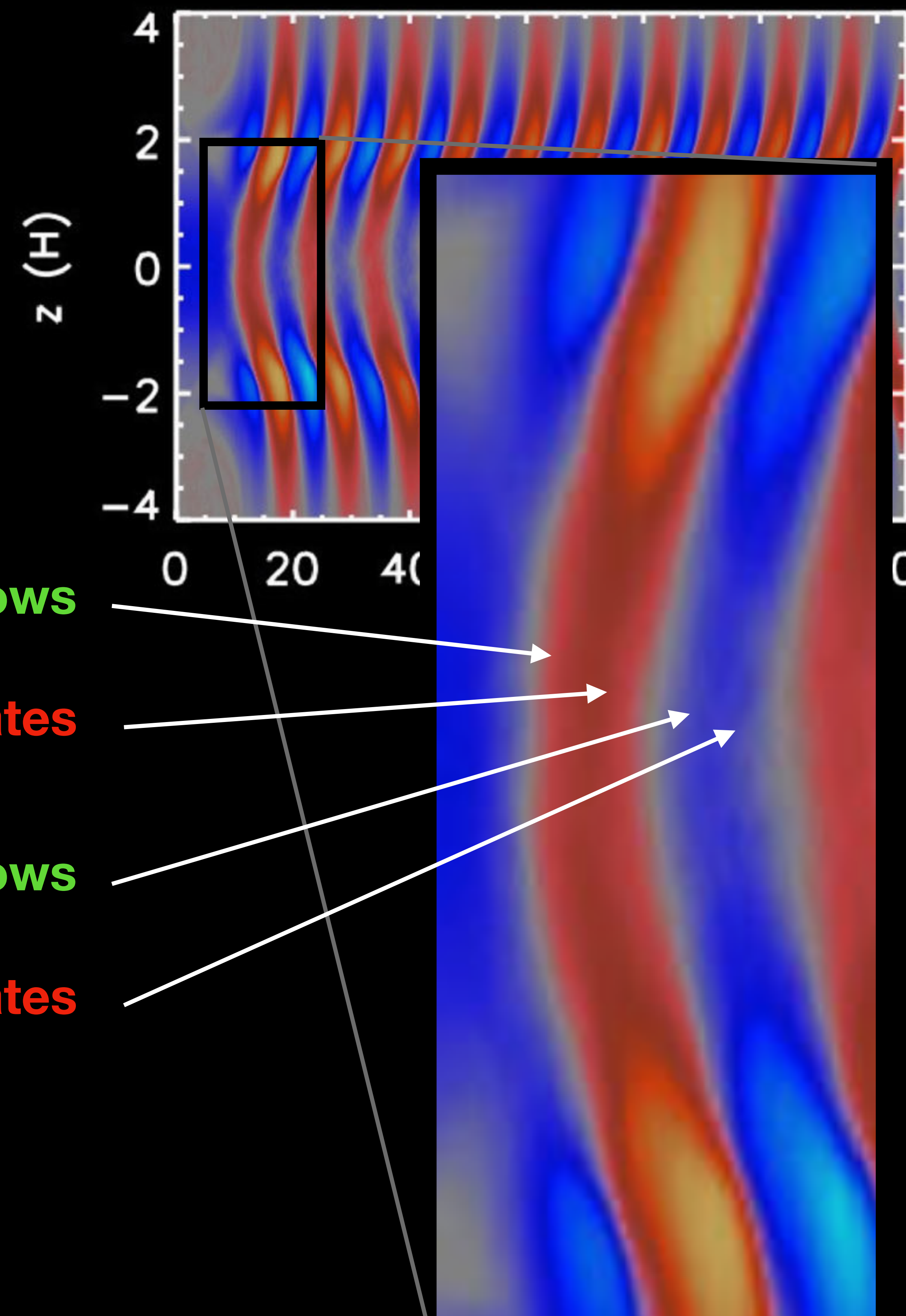

MSC Dynamo Grows

Dynamo Saturates

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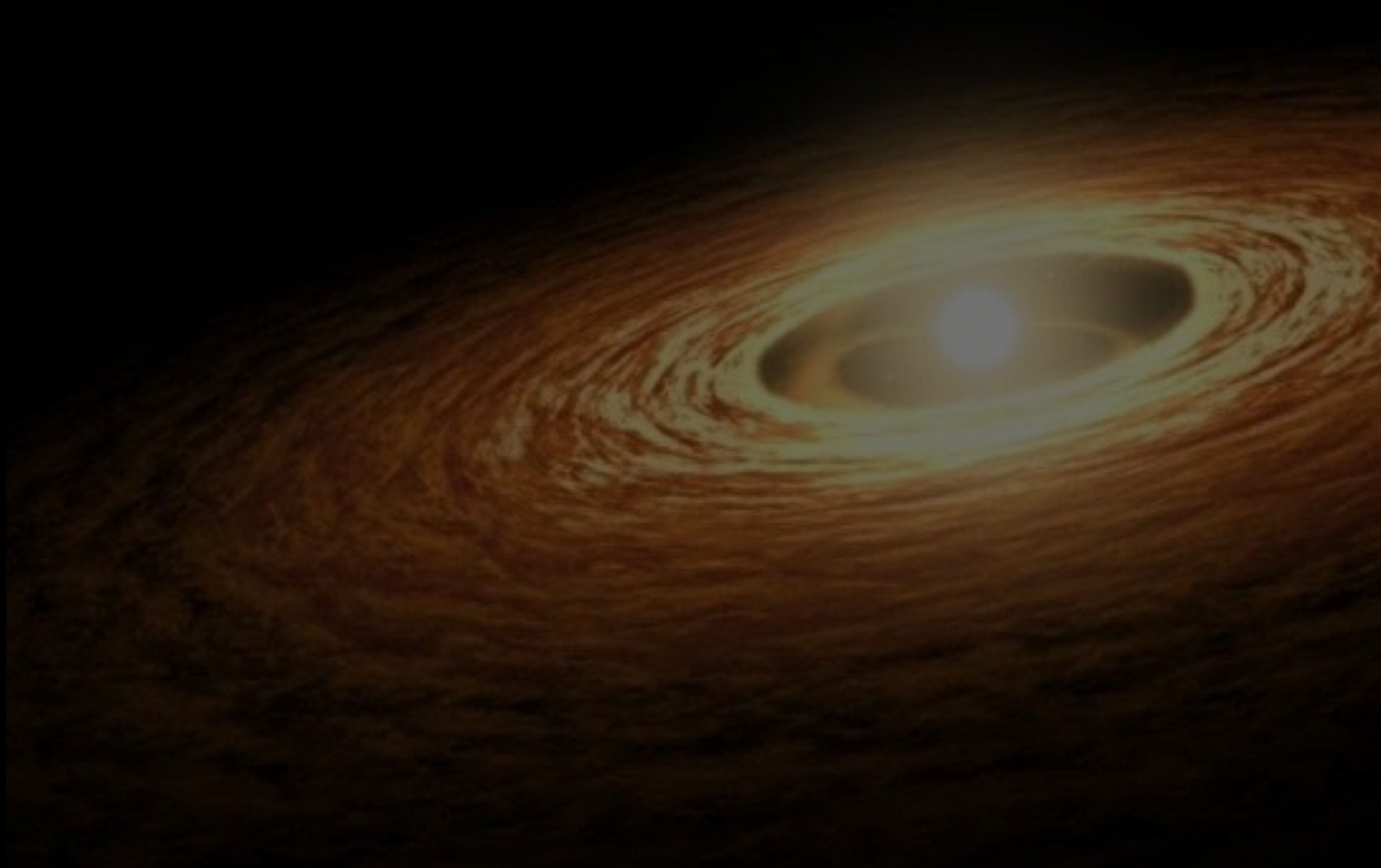
Dynamo Saturates

- Influence of stratification, other physics

Parting thoughts



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- MRI turbulence may be very common throughout the universe.

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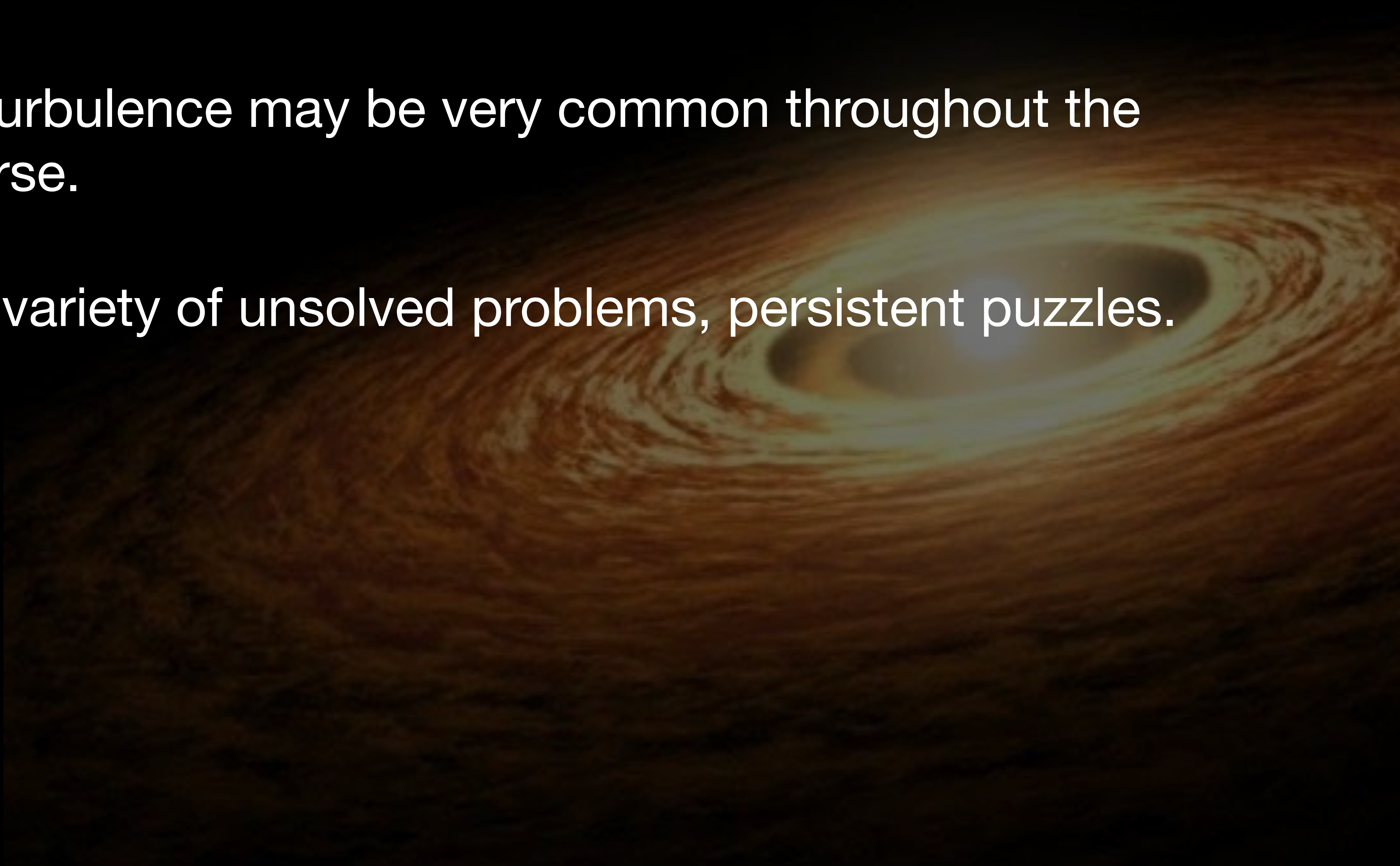

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- Wide variety of unsolved problems, persistent puzzles.

Parting thoughts

- MRI turbulence may be very common throughout the universe.
- Wide variety of unsolved problems, persistent puzzles.
- Next frontier: collisionless MRI turbulence. Soon to see 10^{12}K plasma at the center of our galaxy.